Radiation Safety

University of Nevada Reno
EH&S

Revised January 2004
Compiled by M. Jo

Table of Contents

1. Radiation Safety Program Organization and Responsibilities

1.1 INTRODUCTION

The University of Nevada Reno (UNR) is committed to provide faculty, staff, and students protection from the hazards associated with the use of radiation in academics and research. UNR, as licensee for the possession and use of radiation sources at the University, recognizes its responsibility to establish appropriate policies and procedures for the safe use of radiation sources. UNR has established a Radiation Safety Committee to develop and implement Radiation Safety policies and procedures, established the EH&S Department to manage all safety functions including radiation safety, and appointed a Radiation Safety Officer (RSO) to manage day-to-day radiation safety program operation. UNR's Radiation Safety Manual describes the organization and responsibilities outlined in UNR's comprehensive Radiation Safety Program, including the radiation services available to each user of a radiation source. The Manual was prepared to be consistent with all applicable Federal and State regulations.

Radionuclides used in research, industry, education and medicine are valuable assets which can benefit mankind if used properly. They can, however, present hazards because of their ability to irradiate and contaminate humans and our environment. As a consequence, persons who use radiation sources must understand the various types of radiation hazards and adhere to regulations and standard practices designed to ensure their safe use.

Radiation sources at UNR are regulated by the State Radiological Health Section in accordance with the provisions of NAC 459.320 through 374.

The radiation protection standard is based on the Linear No-threshold Theory, even though it is not a scientifically proven theory. As a result, it is assumed that there is no safe amount of radiation and that any radiation exposure has a certain risk even though it may be small. Therefore, it is the responsibility of all radiation users to avoid all unnecessary and avoidable radiation exposure to himself/herself and others. This is called "as low as reasonably achievable" or ALARA principle.

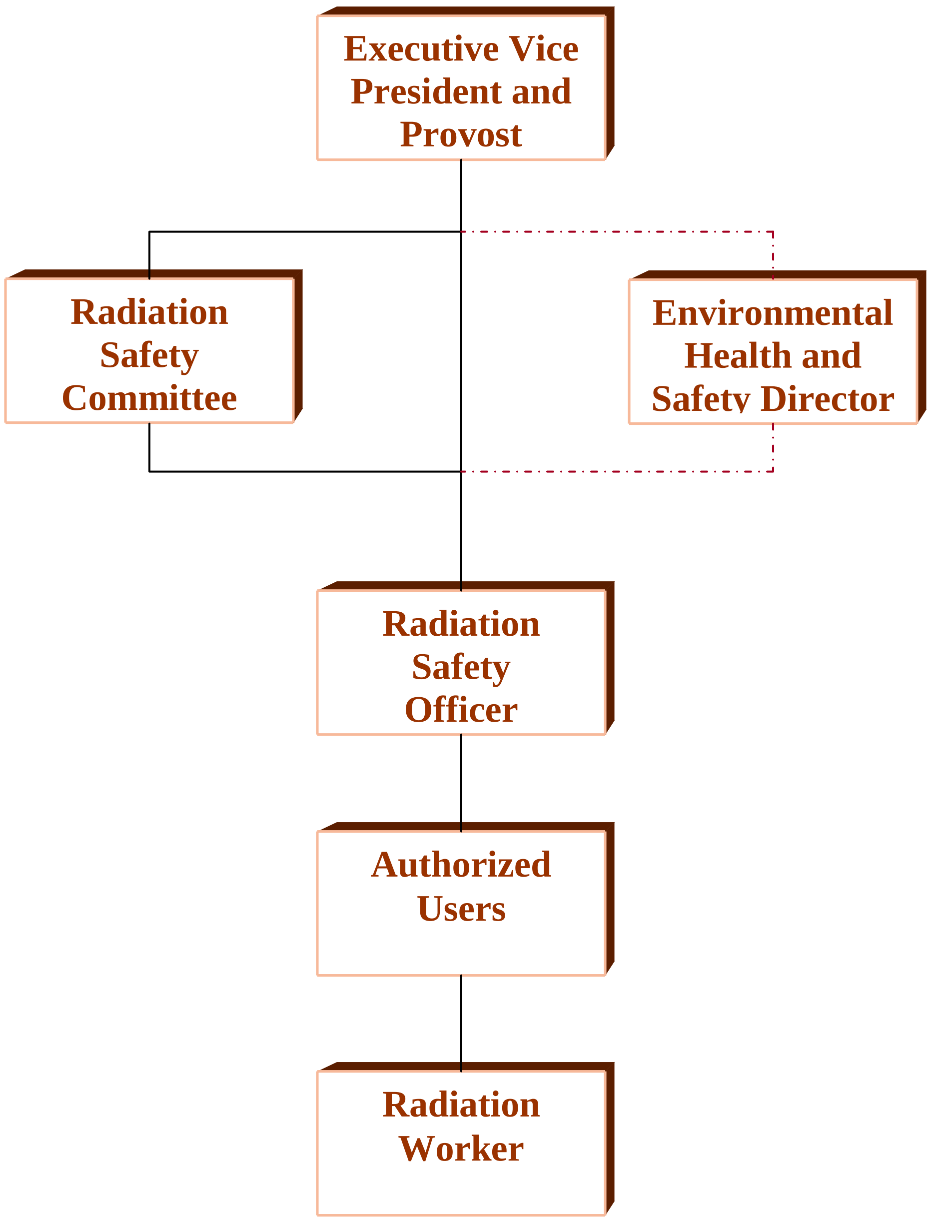
1.2 ORGANIZATION and RESPONSIBILITY

1.2.1 Radiation Safety Committee (RSC)

Membership

The RSC is appointed by UNR management. It advises the UNR management on all matters relating to radiation safety. The committee includes the Radiation Safety Officer (RSO); a representative of management; and members who represent broad areas or divisions of UNR which are likely to use radiation sources, and is thus a mechanism for dissemination of information to the various possible users. The RSO is a permanent member of the RSC and of all of its subcommittees.

ORGANIZATIONAL CHART



Committee Responsibilities

The RSC establishes appropriate policies and procedures to ensure control of the procurement and use of byproduct materials, completion of safety evaluations of proposed uses and users, and the overall development and implementation of the radiation safety program. Any new user must be approved by RSC before first use.

The committee is responsible for assuring that an adequate safety program is developed. The RSC may delegate its authority to various persons and subcommittees with specific expertise in areas under their purview.

The committee delegates its authority to the RSO to review and approve/disapprove requests of a routine nature relating to the use of radiation sources.

The committee meets as often as necessary, but not less than quarterly.

1.2.2 EH&S

The EH&S Department consists of four components of safety programs. They are Radiation Safety, Industrial Hygiene/Occupational Safety, Hazardous Waste Operations (Hazardous Material Office), and Safety Training Coordination. The comprehensive EH&S program is managed by a Director who reports directly to the Vice President for Research. Supervisors of the four functional units are directly responsible for their operations. Technical services and training offered to the campus are internally complementary and solutions to many problems in laboratory and workplace environments result from a coordinated team approache.

The EH&S Department provides the following services

Receipt & issue of radioactive source
Personnel monitoring
Radiation and radioactivity monitoring
Radiation instrument calibration
Waste pick-up and disposal
Transportation and shipping assistance
Emergency assistance
Radiation safety training

1.2.3 Radiation Safety Officer

The Radiation Safety Officer shall be the committee's authorized representative regarding measures concerning radiation safety within the jurisdiction of UNR's radioactive material license.

The RSO in addition to administering and directing the day-to-day operations of the Radiation Safety Program, reviews all applications to use radiation sources and advises the RSC.

1.2.4 Authorized User

An individual is designated an Authorized User by the RSC after careful consideration of his/her training and experience relative to radiation sources. He/she must apply and receive written authorization before conducting any activity involving radioactive material. The Authorized User shall have the primary responsibility for insuring the safe use of the radiation source and compliance with applicable rules and regulations. He/She must also insure that any person acting under his/her supervision is trained in accordance with requirements of the university policy and is aware of the radiation hazards associated with the activity of the materials in use. Application forms, procedures, and additional requirements are specified in the EH&S webpage and in the Radiation Safety Manual. Authorized user permits are for 5 years based on evaluation of the radiation safety record by the Radiation Safety Office. The user must reapply for the new user permit before the current permit expires.

1.2.5 Radiation worker (Persons working under the supervision of an Authorized User)

Persons working under an Authorized User must follow the policies and procedures of UNR and the laboratory. They must use radiation sources only under the supervision of the Authorized User and in the manner specified in the application for authorization to use such source(s). Before working with radiation sources, any user must have received radiation safety training in accordance with UNR requirements.

2. Atoms, Radioactivity, Radioactive Decay, and Radiation

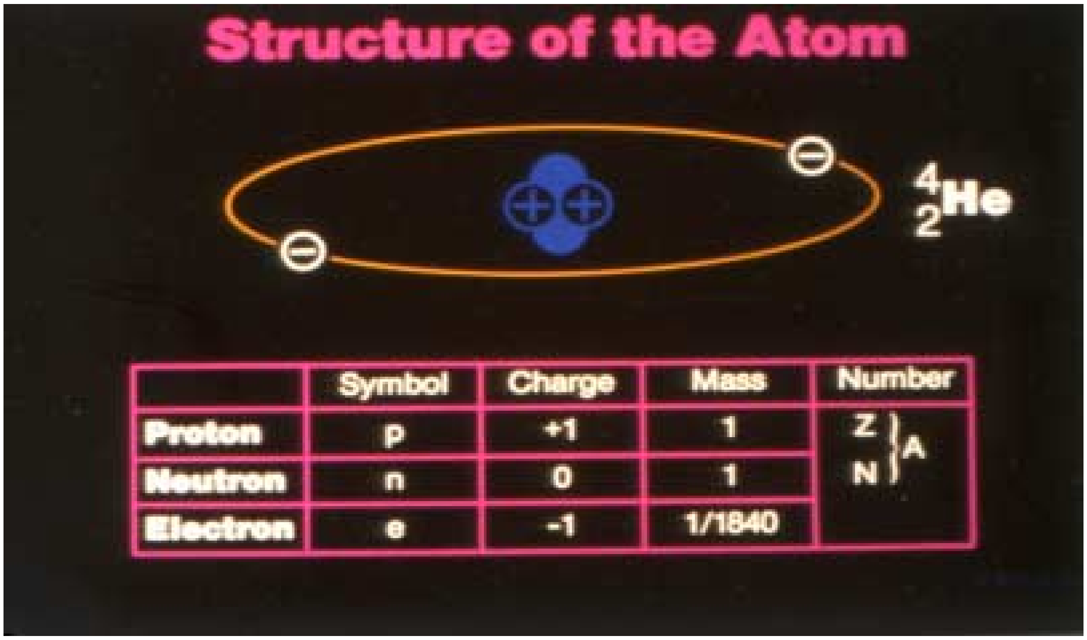
2.1 Atomic Structure

There are hundreds of thousands of different materials we know which appear to have little in common. But if we dismantle these materials, we would find various combinations of different atoms. There are a little over one hundred different types of atoms. If we could take atoms apart we would find combinations of only three kinds of elementary particles. The three basic particles are called proton, neutron, and electron.

- Proton: Protons are an elementary particle with a single positive charge of 1.6022×10^{-19} Coulomb and a rest mass of 1.6726×10^{-27} kg.

- Neutron: Neutrons are an elementary particle with no electric charge and a rest mass of 1.6749×10^{-27} kg.

- Electron: Electrons are an elementary particle with a single negative charge of -1.6022×10^{-19} Coulomb and a rest mass of 9.10946×10^{-31}



These three elementary particles, protons, neutrons, and electrons, of many different combinations form atoms which are called elements or pure substances. An atom is the smallest portion of an element that still has all the characteristics of the element itself. Atoms combine to form molecules.

An atom consists of the nucleus and the orbiting electrons. The nucleus is in the center of the atom with protons and neutrons tightly bound together in the nucleus. The electrons orbit and form a series of shell far outside the nucleus.

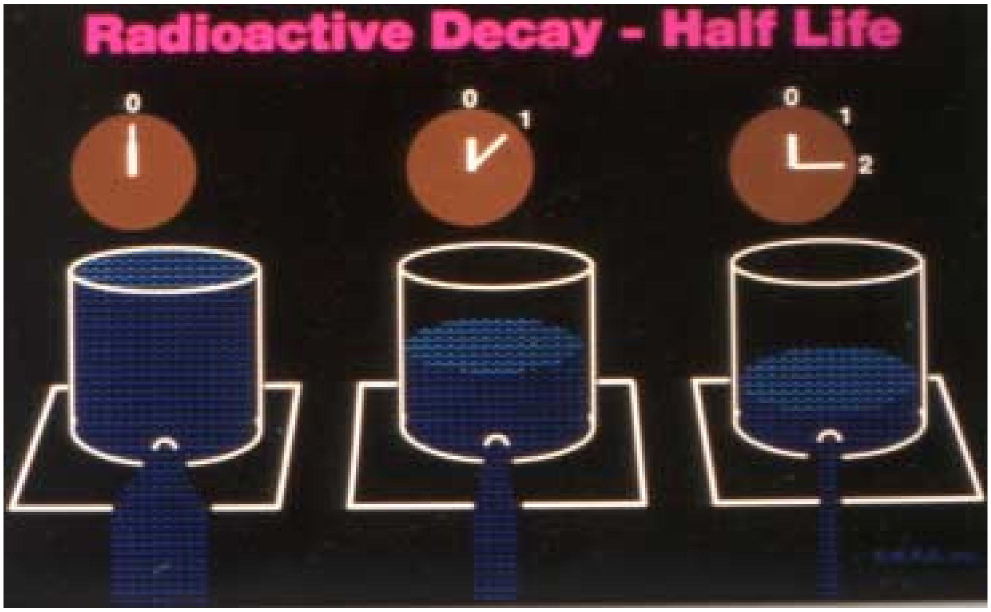
The size of an atom is the average radius of the orbit of the outer electrons. The radius of an atom can be as much as 100,000 times larger than the radius of the nucleus. The radius of a nucleus is about 10^{-15} m. If the radius of a nucleus were 2.5 cm or 1 inch then the outer electrons would be located 2.5 km or 1.5 miles away. An atom is actually mostly empty space with essentially all of its mass concentrated in the nucleus.

Many atoms in nature are unstable and have more mass and/or energy in them than necessary to be stable (ground state). All unstable atoms strive to be at ground state. In the process of getting to a ground state, they emit excess mass or energy in the form of radiation. Radiation can be high energy particles or electromagnetic waves similar to sunlight but of higher energy level. This process is called radioactive decay. Radioactive atoms rearrange their nuclei during radioactive decay and they may change to a different atom. The amount of radioactivity in a sample is measured by the number of atoms decaying per second. The rate of radioactive decay depends on the physical half-life.

2.2 Radioactive Decay and Half-Life

Radioactivity of a sample decreases with time. The more active a sample is, the faster its activity decreases. The rate of radioactivity decrease depend on the half life.

2.2.1 Half-Lives



Physical Half-Life

The physical half life is defined as the time it takes for the radioactive atoms in a sample to decrease to half of their original quantity. Radioisotopes have unique half lives. The range of half lives are from small fractions of second to billions of years.

The radioactive decay equation is:

$$A(t) = A(0)*e^{-(\ln 2/T_{1/2})*t}$$

- $A(t)$: Radioactivity at time t
- $A(0)$: Radioactivity at time 0 (or original activity)
- ln2 : Natural log 2 (numerical value=0.693...)
- $T_{1/2}$: Radioactive half life
- t : Elapsed time between $A(t)$ and $A(0)$

Note: $T_{1/2}$ and t must have the same units of time

Example: If a laboratory has 20 mCi of P-32 today, what is the expected activity in 20 days? P-32 has 14.3 day half life.

$A(t) = 20\ mCi*e^{-(\ln 2/14.3)*20} = 7.59\ mCi$.

Biological Half-Life

The biological half-life is the time required for a biological system to eliminate, by natural process, half the amount of a substance such as radioactive materials or chemicals that enters the system.

Effective Half-Life

The effective half–life is the net effect of the physical and biological half-life combined together in removing the radioactive materials from the body. The effective half-life is always shorter than the physical or biological half-life.

Effective half-life (T_{eff}) = (T_p x T_b)/(T_p+T_b)

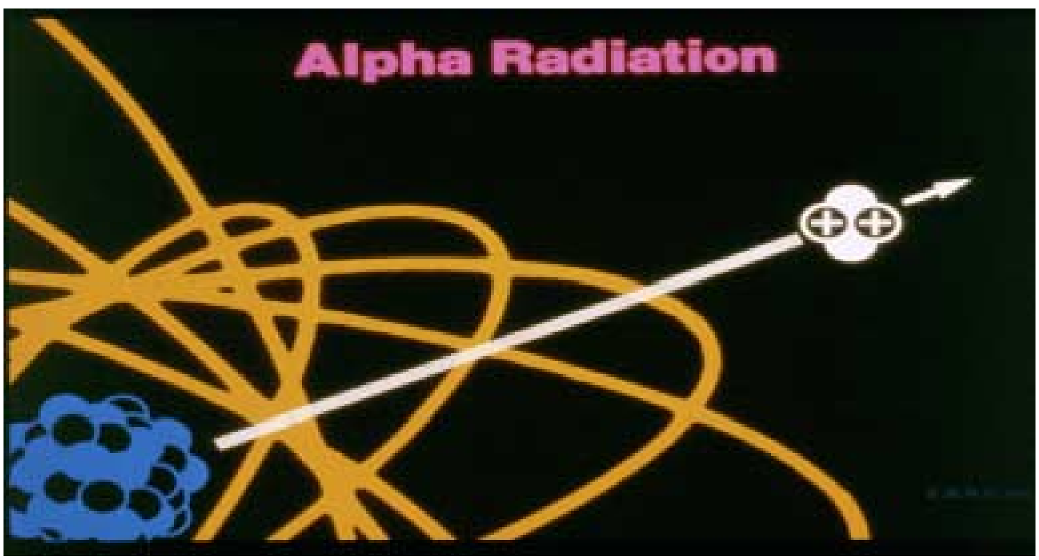
> T_p: physical half-life
> T_b: biological half life
> Note: T_p and T_b are in the same unit

Example: H-3 has 12.33 year physical half-life and 12 day biological half life. The effective half-life of H-3 is:

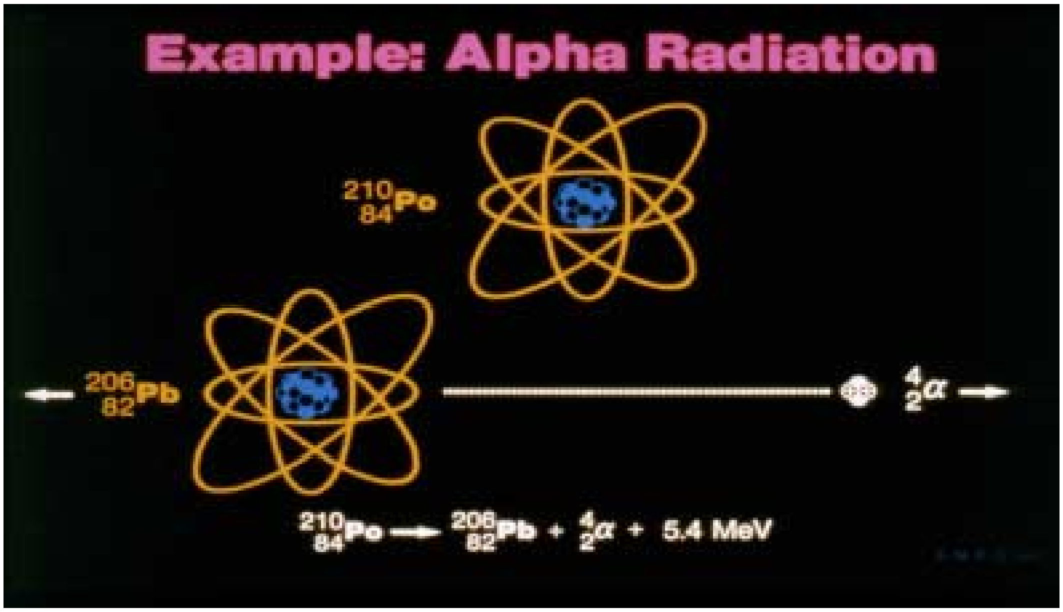
$$T_{eff} = ((12.33\text{ y} \times 365\text{ d/y})(12\text{ d}))/((12.33 \times 365)+12) = 11.97\text{ d}$$

2.3 Types of Radiation

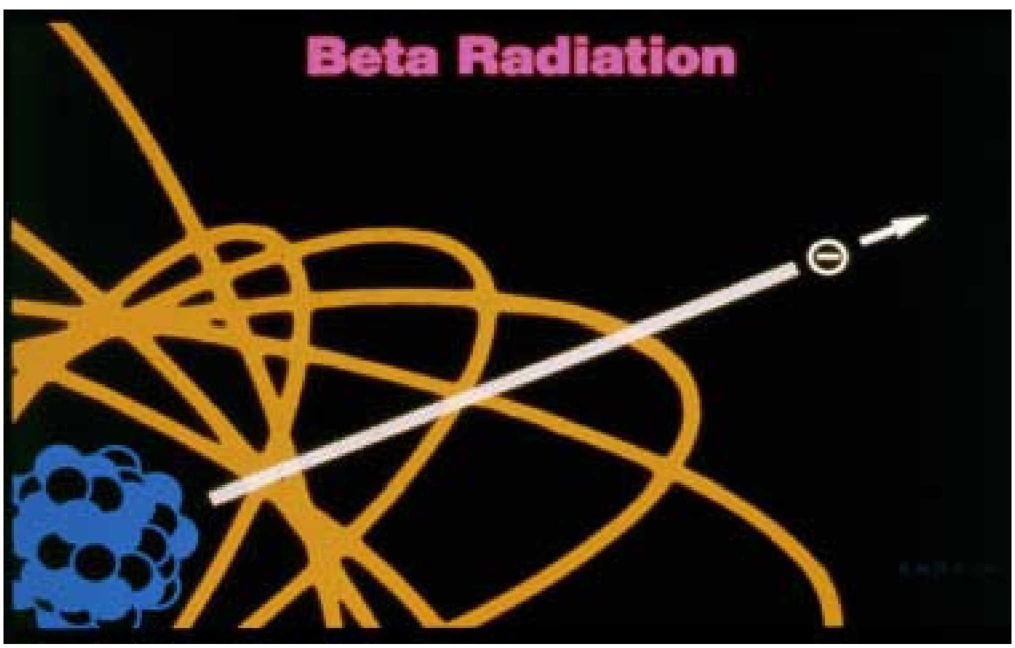
Alpha Radiation



Alpha radiation is a particle ejected at high speed from the nucleus of some radioactive atoms as they decay. An alpha particle is a cluster of four particles, two protons and two neutrons, and has a charge of positive two. An alpha particle is identical to a helium nucleus traveling at high speed. Due to their mass and electrical charge, alpha particles slow down very quickly and don't penetrate very far. Alpha particles cannot penetrate the dead layer of skin that covers the body. Therefore, alpha radiation poses no hazard when emitted from outside of the body. Almost all alpha emitters are naturally occurring radioactive material such as uranium, thorium, and their progenies. Alpha emitters are usually mixed with other types of radiation such as beta and gamma radiation.



Beta Radiation

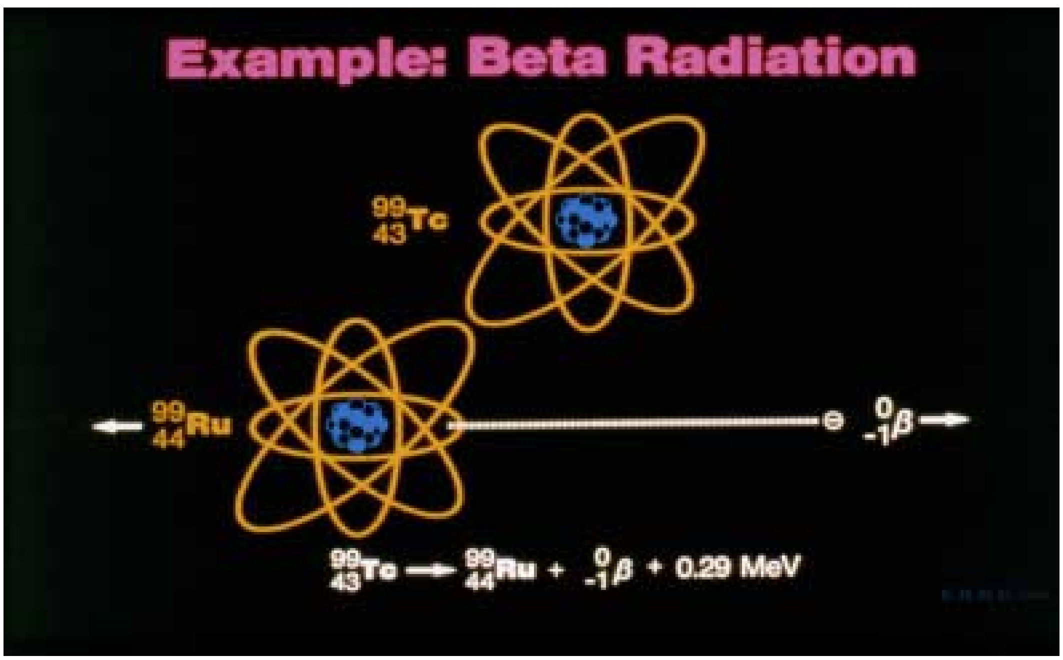


A beta particle is identical to an electron except that it comes from the nucleus, not the outer shells. The beta particle has a charge of minus one and mass of 1/7347 of an alpha particle. For this reason, beta particles can penetrate much farther than alpha radiation.

Energetic beta particles can penetrate the dead outer layer of skin and cause damage to live tissue. Although beta particles are more penetrating than alpha particles they cannot penetrate to internal organs. Beta particles emitted from external sources close to the body may damage live cells of the skin and the lens of the eye. Most radioisotopes used in biological and medical research are beta emitters.

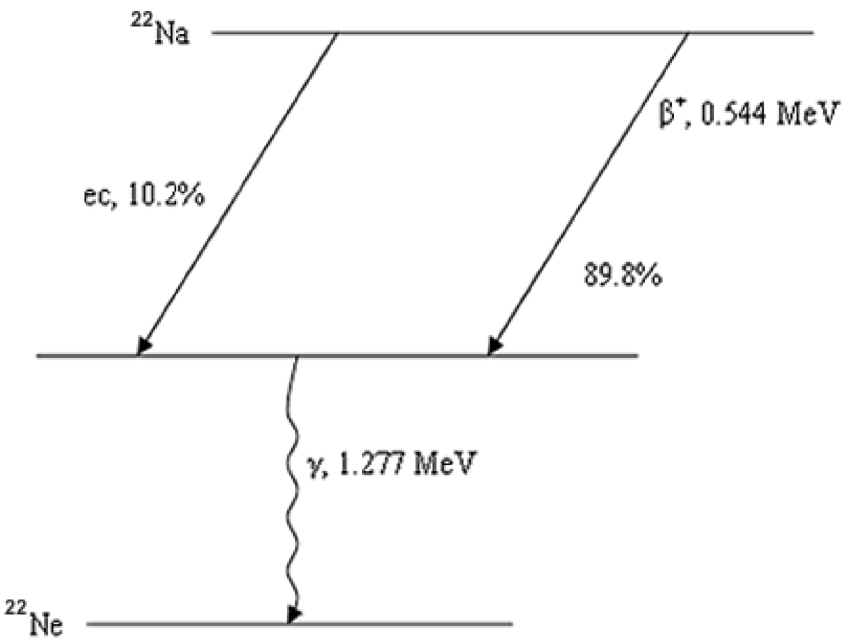
In beta decay, a sub-atomic particle called antineutrino is simultaneously emitted with a beta particle. The antineutrino has little or no mass and no charge. Available energy during beta decay is shared between a beta particle and an antineutrino in all possible ratios. This is the reason why the betas do not have discrete energy, rather the beta particles have a continuous spectrum from zero to its maximum energy. The antineutrino has such an extremely low probability of interaction with matter that there is no easy way to detect it. Normally the average beta energy is considered to be 1/3 of the maximum beta energy.

Examples are H-3, C-14, P-32, P-33, S-35, and Ca-45.

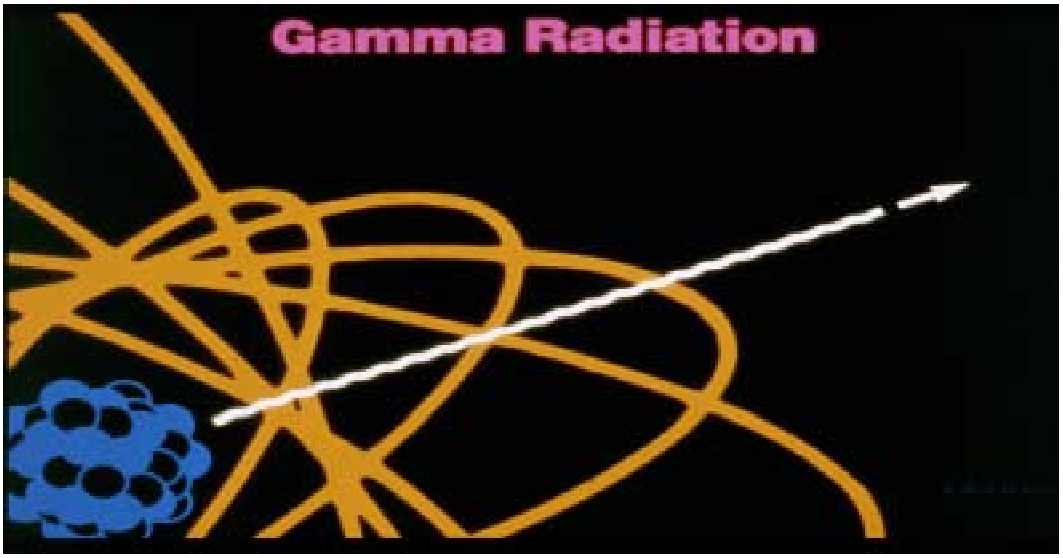


Positron interactions are similar to those of beta particles except that the charge of positrons are the opposite of electrons, i.e. plus-one. In positron decay, a sub-atomic particle called neutrino is simultaneously emitted with each positron particle. The neutrino is identical to the antineutrino previously described except for its spin, which is the opposite direction of the antineutrino's spin. Sodium-22 decays to Neon-22 with positron emission

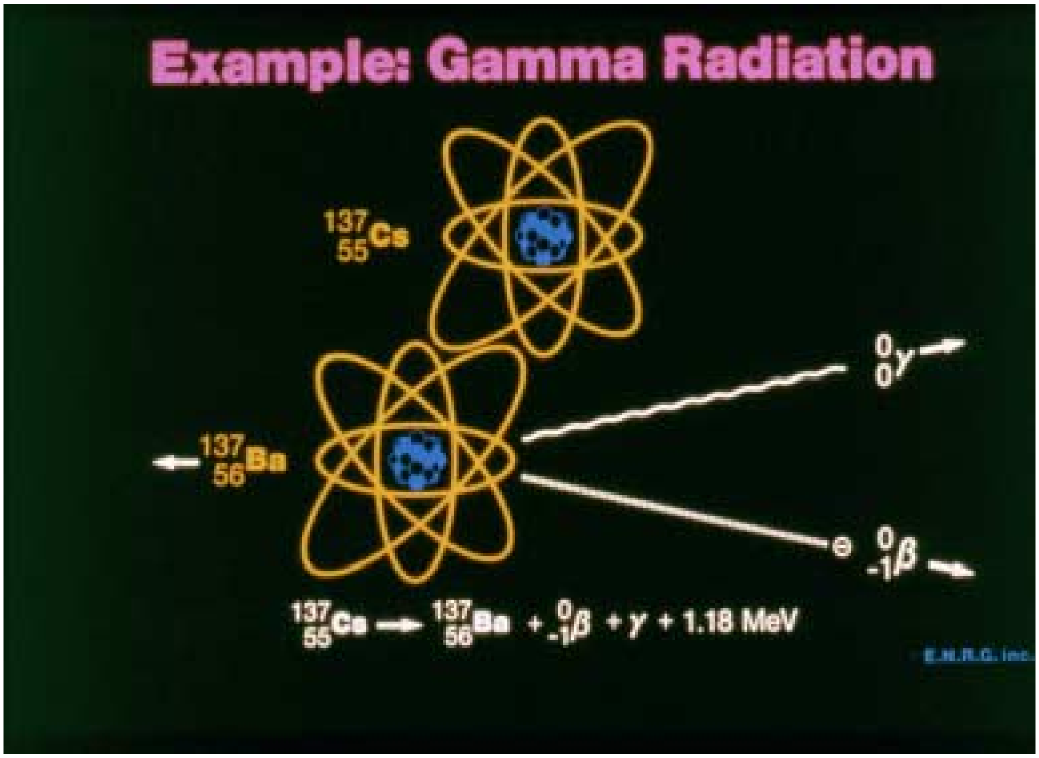
$$_{11}Na^{22} \dashrightarrow {}_{10}Ne^{22} + {}_{1}\beta^{0} + \text{neutrino} + \text{gamma}$$



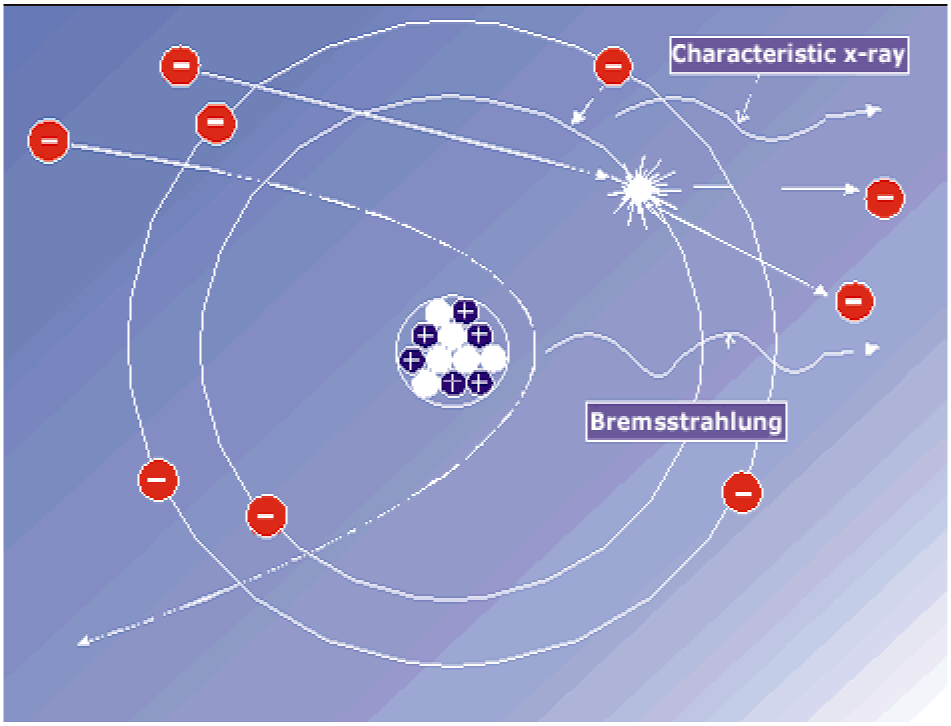
Gamma Radiation



Gamma rays are different from alpha or beta radiation in that they are electromagnetic waves, not electrically charged particles. They are the same as light waves or radio waves except that they have much more energy. Gamma rays are just like x-rays except for where they originate. Gamma rays, like alphas and betas, come from the nucleus of a radioactive atom. X-rays come from outside the nucleus. Because gamma rays and x-rays have no charge and no mass, they are able to penetrate deeply through materials. Commonly used gamma emitters used in research are Cr-51, Fe-59, I-125, and I-131.



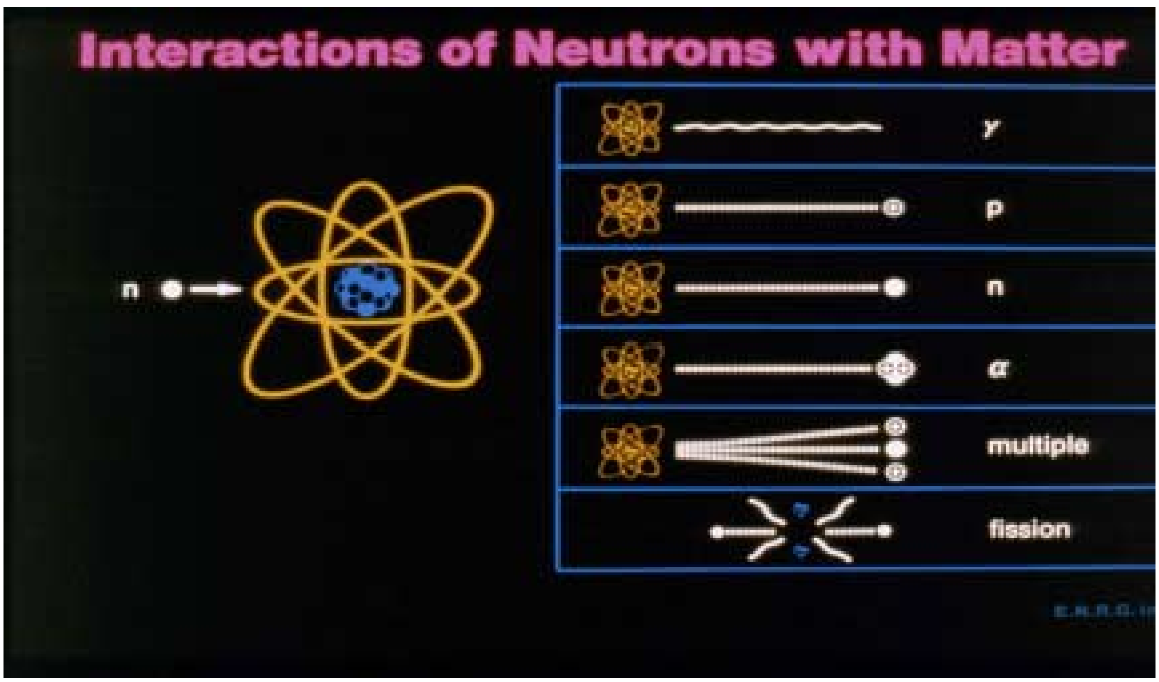
X-rays



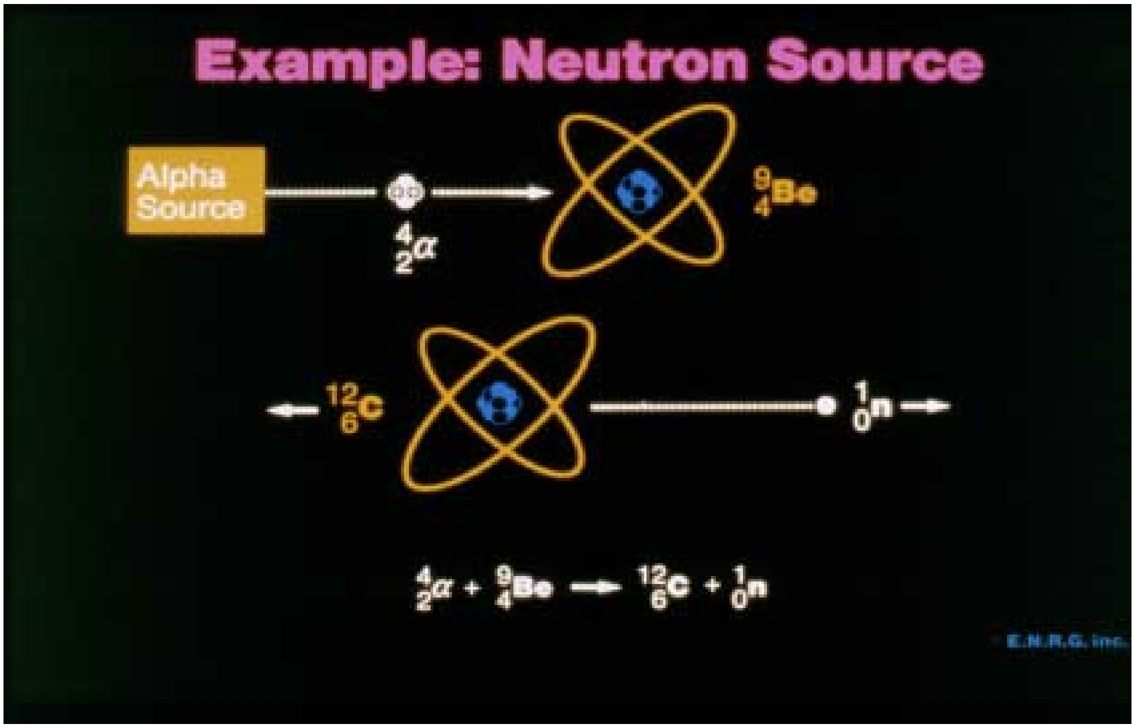
Electrons move around the nucleus in fixed orbits. Each shell corresponds to a particular energy "binding" the electron in that shell. The closer the electron is to the nucleus, the higher the binding energy. When a vacancy occurs in a shell due to a decay or a collision, a transition can occur where an electron in one shell moves to another. This causes the emission of an electromagnetic ray or radiation with an energy equal to the difference in energy between the two shells. These radiations are called characteristic x-rays because the energy of the ray is characteristic of the type of atom.

The second way in which x-rays are produced is called bremsstrahlung. Whenever charged particles are accelerated (or decelerated) an electromagnetic ray is emitted. Electrons are accelerated around the nucleus of atoms because of the attractive force of the opposite charges. This occurs when electrons reach high velocities, such as in an x-ray tube, and hit a dense target (high atomic number). This is how x-ray machines produce x rays. Another way this can happen is if beta emitting radioactive material is placed close to or contained in a dense material such as lead. Bremsstrahlung is more likely when the charged particle has little mass, high energy, and when the target is dense.

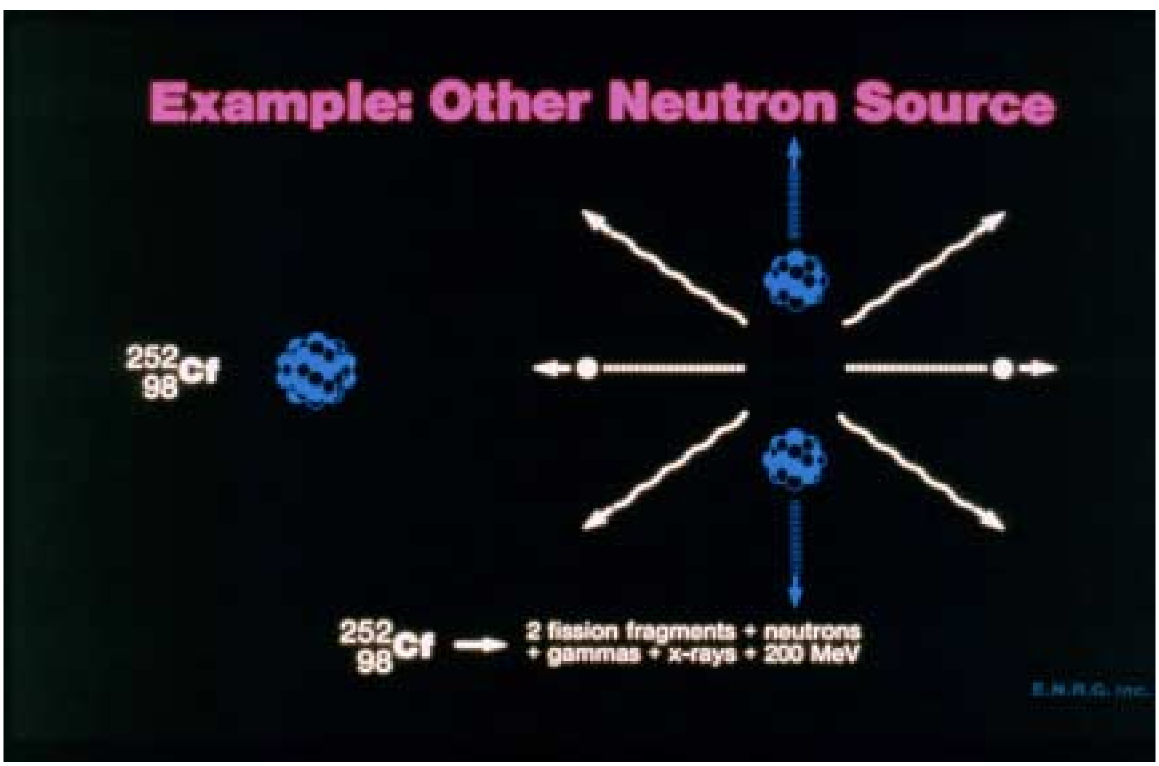
Neutron Radiation



Neutrons can be emitted during nuclear reactions and, they can be emitted by decay of certain radionuclides, although this rarely occurs with naturally occurring radionuclides. Neutrons, because of their large mass and neutral charge, can be absorbed or scattered by the nucleus of atoms they interact with. When neutrons are absorbed, nuclear reactions, such as fission, are possible and often result in the emission of secondary radiation. In this indirect manner, neutrons cause effects similar to those caused by other radiation. ^{241}Am-Be, ^{239}Pu-Be, and ^{226}Ra-Be are commonly used neutron sources. The alpha particles from ^{241}Am, ^{239}Pu, and ^{226}Ra hit the target of ^{9}Be to produce an alpha-neutron reaction(a,n). One Ci of ^{239}Pu-Be alpha source will produce 2.1 x 10^6 neutrons/second and 2.6x10^6 neutrons/second are produced by one Ci of an ^{241}Am-Be alpha source

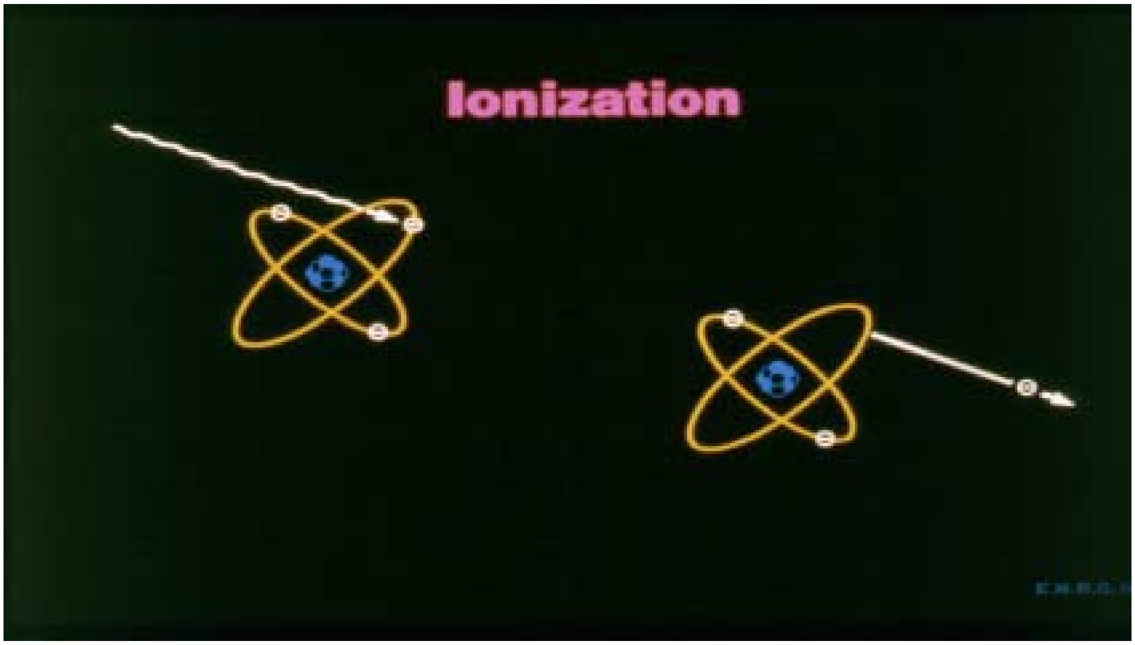


Cf-252 is the only spontaneous-fission neutron source with practical applications due to its reasonably long half life (2.65 years). Also, nuclear reactors and some accelerators are sources of neutrons. Particle accelerators can produce neutrons by striking a tritium target with deuterons



3. Radiation Interactions with Matter

A significant characteristic of radiation is that radiation can ionize atoms. Most atoms are electrically neutral, that is they have same number of protons (+ charges) and electrons (- charges). Radiation has the ability to directly or indirectly cause electrons to be removed from atoms. This creates a pair of charged particles. One is negative electron; the other is the remaining atom, now positively charged. This process is called ionization.

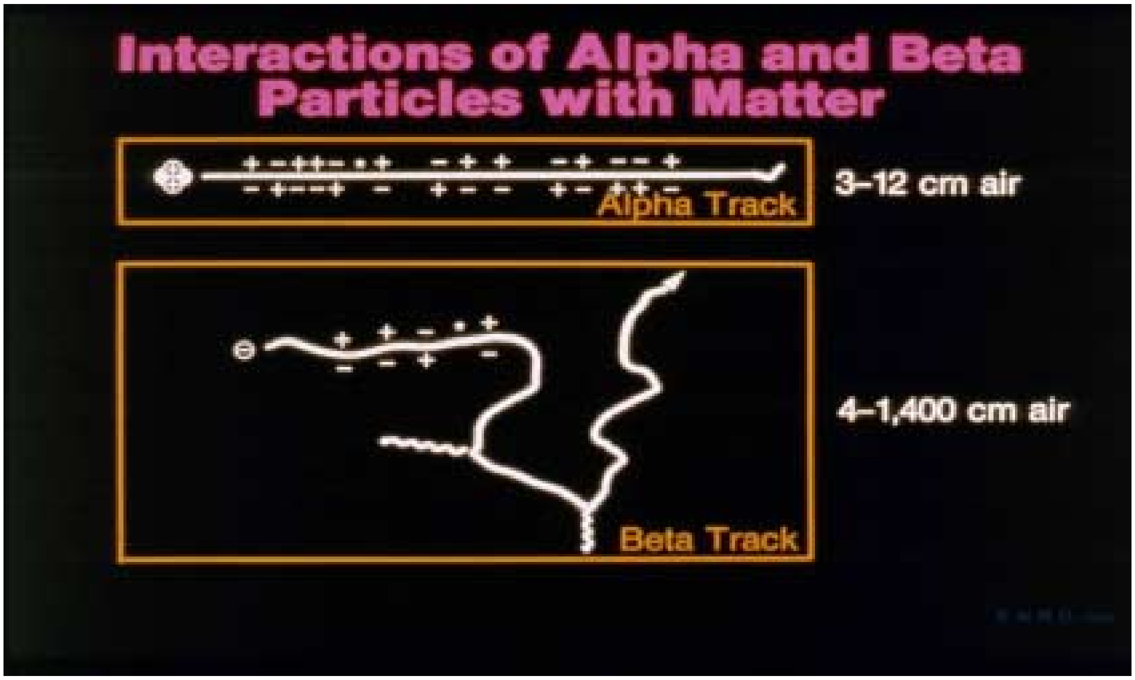


3.1 Alpha Radiation Interaction with Matter

The alpha particle follows a straight, short path in the material it penetrates, causing very dense ionization and excitation events along the track, in orders of millions per inch. Most alpha ranges are less than 5-6 cm in air. Alpha particles can be stopped by a sheet of paper.

3.2 Beta Radiation Interaction with Matter

The beta particle track is very different from the short, straight alpha track. The beta particle scatters frequently, causing what is often described as a drunken man's path. The range of a beta particle is considerably greater than an alpha particle. As a rule of thumb, one MeV beta particle can travel about 10 feet in air or about 0.4 cm in water. The ionization and excitation events along the path are much less than that due to alpha particles, yet the amount is still large, thousands to hundreds of thousands per inch. Additionally, the high energy betas near dense material can generate bremsstrahlung x-rays which is much more penetrating than the beta particle itself. The production of bremsstrahlung x rays increases with the atomic number of the target material and beta energy. Therefore, low Z material such as Lucite and plastic (large hydrogen, atomic number 1, population) are used as a beta shield.

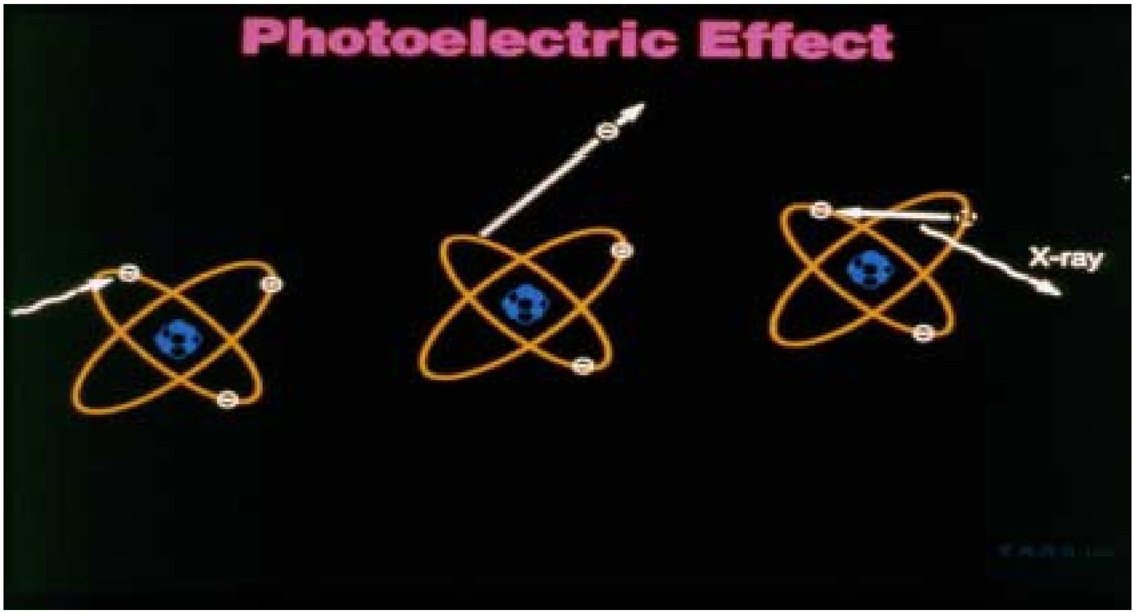


3.3 Gamma and X-ray Interaction with Matter

The predominant interactions that occur between gamma or x rays and atoms of matter depend on the photon energy and the atomic number of the material. The word photon is used to imply the particle-like behavior of an electromagnetic wave. The photon can be absorbed by what is called the photoelectric effect; it can be scattered by Compton scattering; and it can be converted to particles of mass by pair production. The photoelectric effect has the highest probability with a low energy photon and a high atomic number absorber. For intermediate energy photons Compton scattering is the most frequent interaction. At higher photon energies, pair production is the predominant interaction. Effective shielding materials from gamma and x-ray are dense material like lead or thick concrete. Leaded glass or plastics are used for low energy gamma and x-ray shielding.

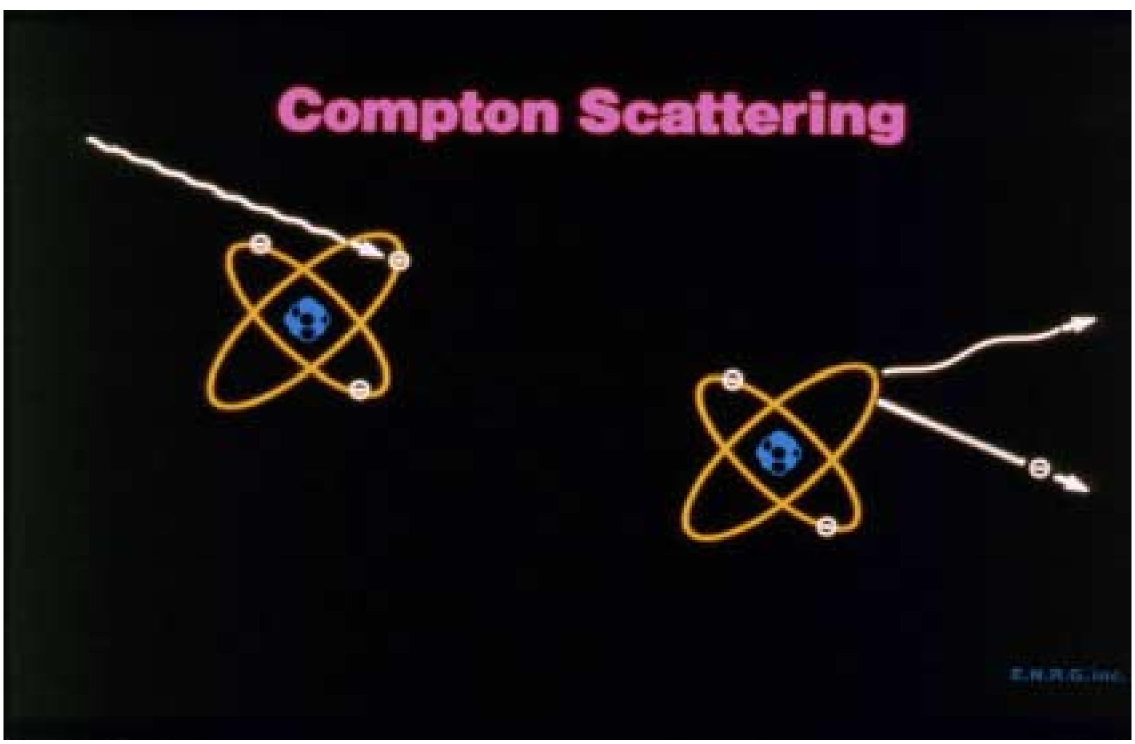
3.3.1 Photoelectric Effect:

The incoming photon is absorbed and imparts all of it's energy to an orbital electron. Then the electron is ejected from the atom. This electron then causes ionization just like a beta particle. Subsequent to the ejection of an inner shell electron, an x-ray is often emitted when the vacancy is filled.



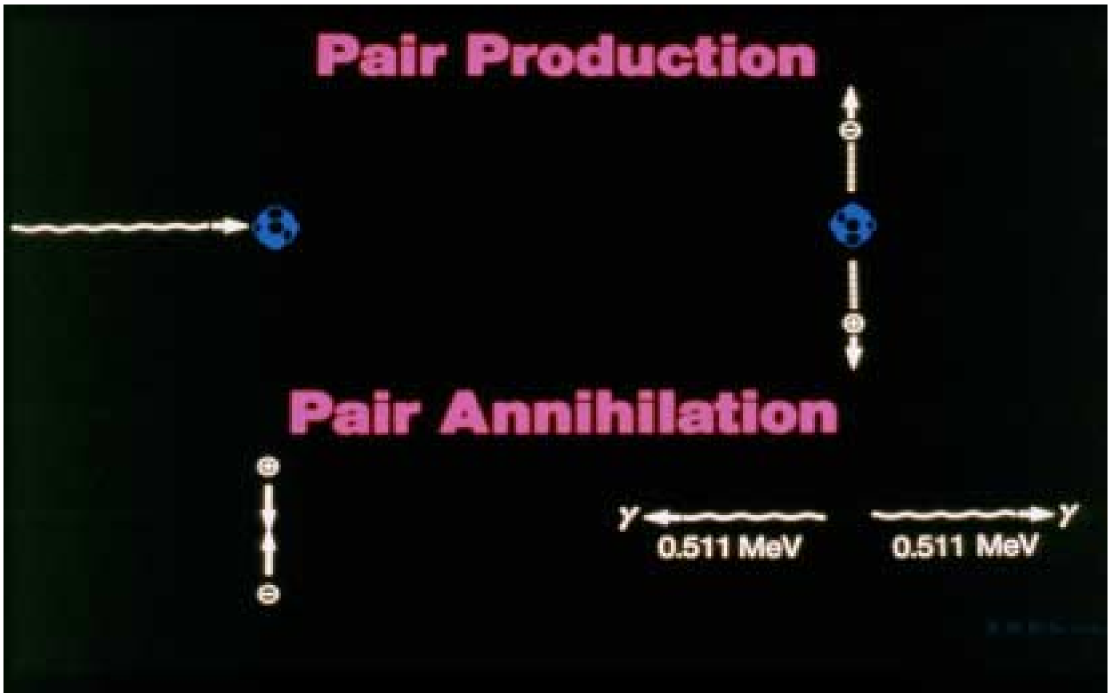
3.3.2 Compton Scattering:

Compton scattering is scattering of a gamma or x-ray by an electron in an atom. The photon changes direction looses partial energy, and the electron is kicked out of the atom. The electron and the scattered photon cause further ionization. The actual energy change depends on the incident energy and the angle at which the photon is scattered. The attenuated photon may experience a photoelectric absorption or another Compton scattering if enough energy remains.



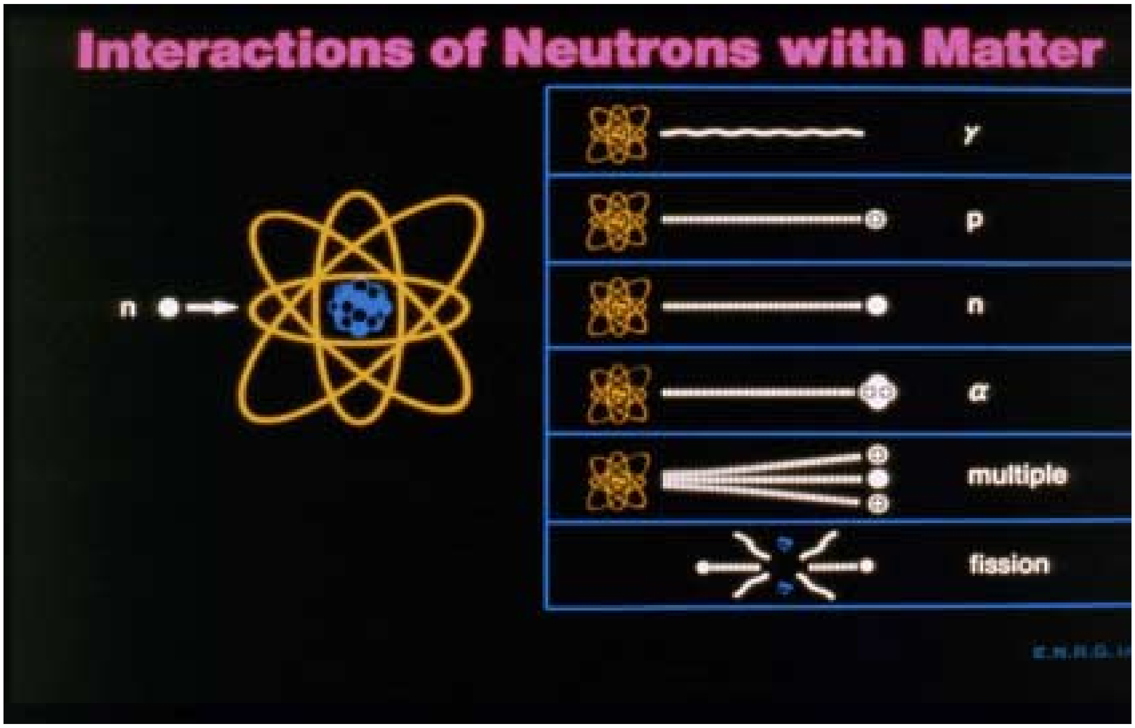
3.3.3 Pair Production:

The incident photon, if energetic enough, vanishes and its energy is transformed into two electrons, one bearing a negative charge, the other positive (positron). Both of these charged particles cause ionization. After the positron has lost most of its kinetic energy, it will quickly react with a nearby electron and both are annihilated. The annihilation photons always have energies of 0.511 MeV. In this process, mass is converted into energy and energy is converted into mass.



3.4 Neutron Interaction with Matter

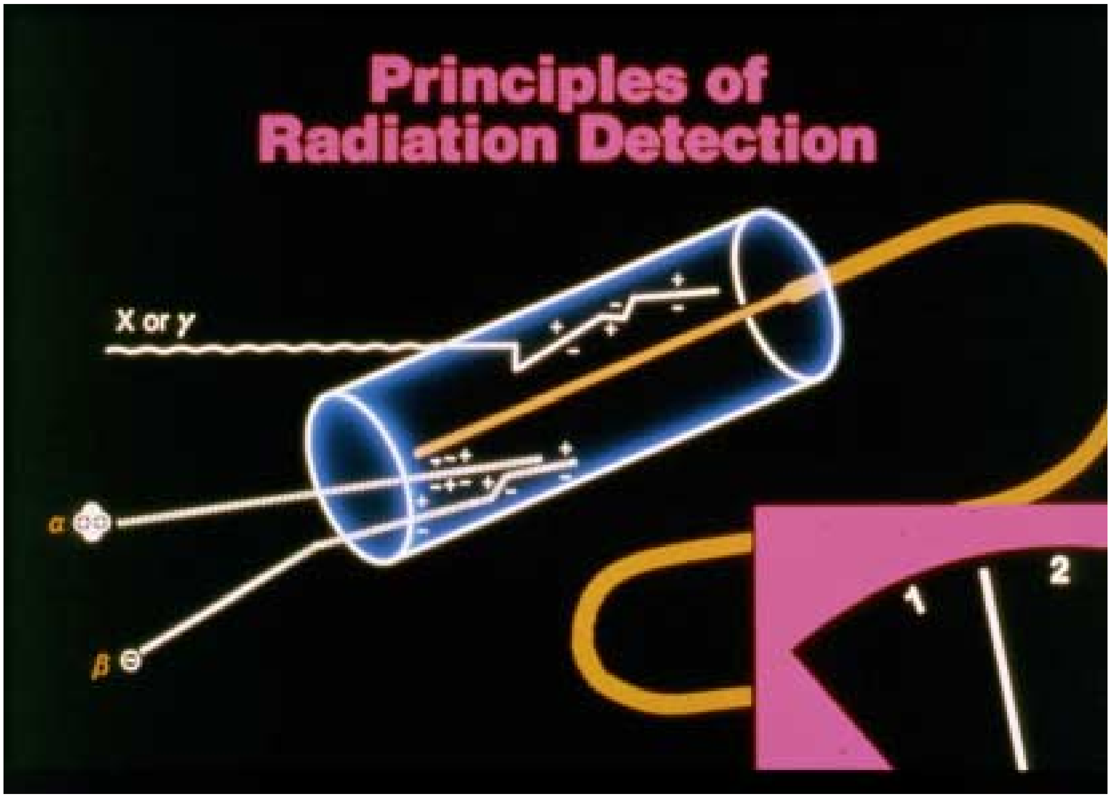
The way neutrons interact with matter depends on neutron energies and the type of absorbing material. Absorption of neutrons is one type of interaction. A neutron is absorbed by the nucleus of an atom and a secondary radiation, gamma or beta, is produced. Another type of reaction is the absorption of neutrons followed by emission of one of the target atom's nuclear components. Neutrons can collide with the nucleus elastically or inelastically depending on the mass of the target. Some atoms like uranium and plutonium can fission as a result of neutron absorption.



4. Radiation Detection Equipment

Radioactive material use laboratories must be equipped with the appropriate radiation detection equipment in good working order.

There are portable detectors and fixed detectors. The term fixed detector here means that the detector system is heavy and stationed in one location. Guiger-Mueller (GM) detectors, ion chambers, and some scintillation detectors are portable. Liquid scintillation counters, gas proportional counters, and solid state gamma spectroscopy systems are usually fixed equipment. There are also portable gamma spectroscopy systems and proportional counters. Fixed equipment has good detector shielding which shields background radiation and extensive electronics which make them heavy.



4.1 Guiger-Mueller (GM) Detector

The GM detector is a gas filled detector. Radiation causes ionization inside the detector and the liberated electrons are collected at the anode in the center of the detector. High electric potential is applied between the anode and the cathode which accelerates librated electrons toward the anode. While moving toward the anode, the accelerating electrons cause a succession of ionization like many avalanches. This process is called gas multiplication. It produces a large numbers of charges. The gas multiplication factor for GM is in the range of 10^6-10^8. The collected charges in the anode generate electrical pulses which are processed through electronics.

The GM detector is a simple, inexpensive, easy to operate, sensitive to low level, and reliable instrument. The three major types of radiation (alpha, beta, and gamma) can be detected by the GM detector. The thin window GM is sensitive to low level radiation and well suited to checking for contamination on one's clothing and body as well as in work areas. Portable survey meters with GM's are usually equipped with a speaker or other audible indicator, to allow surveys without watching the meter. GM detectors come in many different sizes. A cylinder type with a beta shield is one type, and a cylinder with thin end window is another type. The "Pancake" GM detector has a 2 inch diameter thin mica window which is a relatively large active detector area. It is capable of detecting alpha, beta, and gamma radiation. Portable survey meters with GM detectors have cpm and/or mR/hr reading scales. Due to the sensitivity of GM detectors, they have a limited range. GM's are not suitable for high radiation fields. Normally, the ranges of GM detectors are 0-50 mR/hr, with some having ranges up to about 200 mR/hr.

GM detectors with thin end windows can detect almost all commonly used radionuclides in research laboratories except Hydrogen-3. The liquid scintillation counter is the most efficient and widely used method to count Hydrogen-3.

4.2 Ion Chamber

An ion chamber is a gas filled detector which is less sensitive to low level radiation fields than GM detectors. The gas multiplication factor is one (1) for ionization chambers and millions for GMs. An ion chamber is normally designed to monitor gamma and x rays. Though there are ion chambers which can detect beta radiation through beta windows, they are not practical in research laboratories where the quantity of radioactive material are small and radiation levels are low.

Ion chambers may be useful in areas where significantly higher radiation levels than background levels exist such as: particle accelerators, x-ray producing machines, and irradiators.

There are ion chambers which can measure background level. Pressurized ion chambers have higher sensitivity and can measure radiation levels from microR/hr to R/hr range.

4.3 Gas Proportional Counter

The gas proportional counter (GC) is a gas filled detector. The operating principle is similar to other gas filled detectors. The gas multiplication factor for GPC is from hundreds up to a million. The output charge is proportional to the incoming radiation energy. A GPC uses different operating voltages for alpha and beta radiation counting therefore GPCs can analyze samples which emit both alpha and beta radiation and distinguish between alpha and beta radiation. GPCs can detect gamma radiation but gamma detection efficiency is much lower than alpha and beta detection efficiency. P-10 gas which is 90% argon and 10% methane is commonly used for a GPC. There are also other gases used in GPCs.

The GPCs are usually fixed instruments which have a heavy detector and sample shield. Some portable contamination monitors are made out of GPCs.

Many GPCs have automated sample exchangers which can handle tens of samples at a time. Therefore, use of GPC can save a considerable amount of time if a large number of samples are to be analyzed.

4.4 Scintillation Detector

There are scintillation detectors for alpha, beta, gamma, and neutron radiation. Scintillators are made of plastic, organics, or inorganic materials. They can be solid, liquid, and gas. They can be made in all shapes and sizes. Scintillation detectors can be used with portable survey meters or fixed equipment. Incoming radiation interacts with a scintillating material and a portion of or the total energy is transferred to the scintillating material. The excited scintillating molecules produce light photons during the de-excitation process. Scintillation detectors may directly count these photons or convert these photons to electric current via photomultiplier tube and measure the current produced by the converted electrons. A sodium iodide (NaI) detector is commonly used for gamma detection and analysis. Due to the high sensitivity, NaI detectors give high background radiation levels. Detector shielding can reduce background radiation level.

4.4.1 Liquid Scintillation Counter

Liquid scintillation counting (LSC) is widely used for low level beta radiation detection. The LSC can detect alpha, beta, and gamma radiation with high efficiency. The sensitivity of LSC is higher than other detectors. The sample is immersed in the scintillating medium and it is in direct contact with the scintillating medium which makes the LSC efficient and capable of detecting low radioactivity levels and low energy radiation. The function of the scintillation medium is to convert the radiation energy into light photons which can be detected by the scintillation counter. The energy of radiation is absorbed by the scintillating medium which causes the molecules to become excited. The excited molecules emit photons and then return to their ground state. The light output is proportional to the incoming radiation energy.

LSC requires use of a scintillating medium. Sample preparation can be time consuming if a large number of samples are needed. But a large number of samples can be counted without attendance because the prepared samples are usually fed automatically. Liquid scintillation counters are large fixed instruments, not a portable system. The scintillation solution is expensive to purchase and to dispose of.

Most tritium counting is done by LSC. Due to its low energy, tritium is extremely difficult to detect.

4.5 Solid State/Semiconductor Detectors

The solid state detectors, such as silicon and germanium detectors, are mainly used for gamma spectroscopy. The main advantage of solid state detectors is very good energy resolution. Gamma detection efficiency of germanium is low but the energy resolution of gamma spectrum by germanium is the best among all detectors. The operating temperature is very low and requires liquid nitrogen to maintain operating temperature. Gamma emitting Isotope identification and quantitation are the main uses for these detectors. The gamma spectroscopy system can be a fixed system or portable system. Normally they are fixed instruments with a thick and heavy shield around the detector and sample to reduce background radiation.

4.6 Personal Monitoring Devices

The film badge and thermoluminescent dosimeter (TLD) are widely used for personal monitoring. The personal dosimeters are exchanged in monthly, bi-monthly, or quarterly. They should be kept in a dosimeter rack away from any radiation sources when not in use.

The whole body dosimeters should be worn at chest or collar area when in use. The extremity monitors such as TLD ring should be worn inside of glove with the label facing towards palm.

The film badge works similar to ordinary photographic film. The film is enclosed in a light-tight packet and radiation penetrates to expose the film. They are not sensitive to low energy betas such as Hydrogen-3, Carbon-14 or alpha radiation. If the packet is damaged or opened then the film badge is invalid due exposure to light.

The TLD is a small crystal. When exposed to radiation, the molecules of the detector material are raised to metastable states by energy received from radiation. They stay in the excited states. When these crystals are heated, these molecules return to its ground states with emission of light photons. The amount of light photons emitted is proportional to the radiation energy absorbed.

Personal dosimeter may only be used for personal monitoring of the person the dosimeter is specifically issued to.

5. Units of Radioactivity and Radiation Measurement

Table 1. Units of radioactivity and radiation exposure

	Traditional units		SI units		Relations
	Unit	Definition	Unit	Definition	
Radioactivity	Curie (Ci)	3.7×10^{10} disintegrations per second (dps)	Becquerel (Bq)	1 dps	1 Ci = 3.7×10^{10} Bq
Exposure	Roentgen (R)	2.58×10^{-4} coulomb per kg of air	R		
Absorbed dose	rad	100 ergs/g	Gray (Gy)	1 joule/kg	100 rad = 1 Gy
Dose equivalent	rem	Rad x quality factor (Q)	Sievert (Sv)	Gy x Radiation weighting factor (W_R)	100 rem = 1 Sv

Table 2. Quality factor (Q) and radiation weighting factors (W_R)

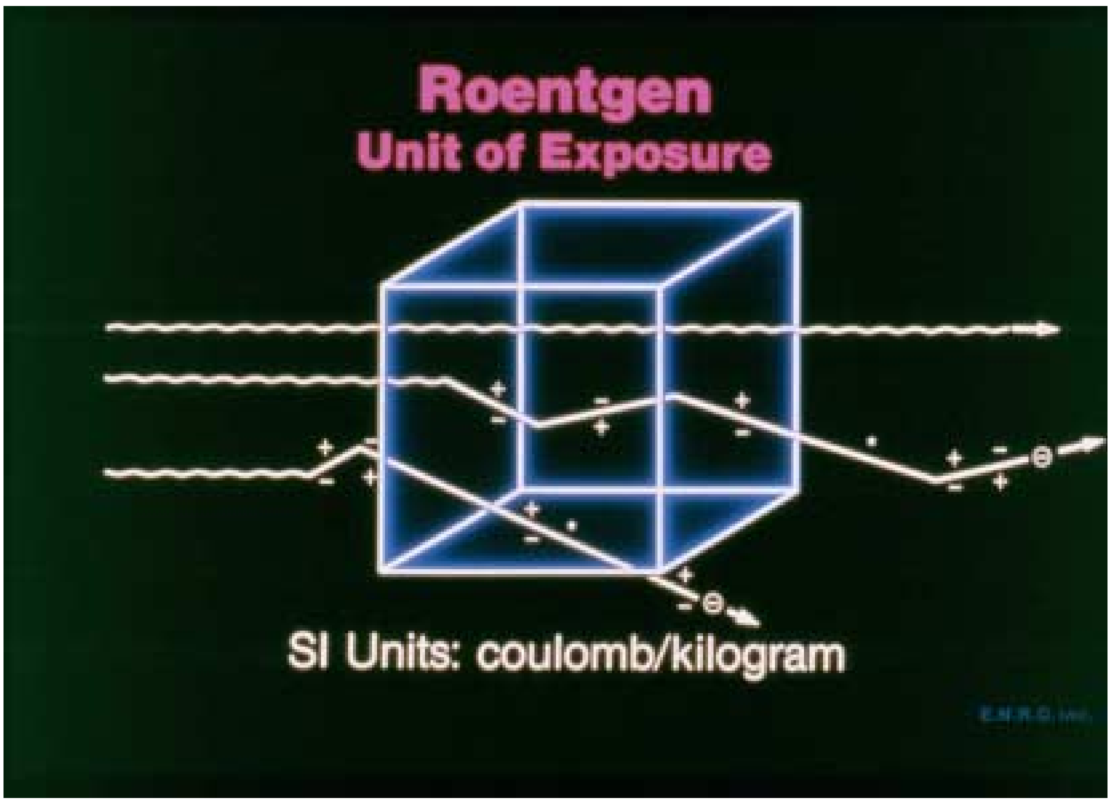
Radiation	Q	W_R
X, gamma, beta	1	1
Alpha	20	20

5.1 Radioactivity:

The Becquerel (Bq) and the Curie (Ci) are commonly used as units of radioactivity. The Bq is defined as one disintegration per second. The Ci is defined as 3.7x1010 disintegrations per second. Commonly used multiples and sub-multiples of the units are mega Bq (MBq, million Bq), giga Bq (GBq, billion Bq), millicurie (1/1000 of Ci), and microcurie (1/1,000,000 of Ci). The half life described in the next section describes how long the radioactive material might last and the number of Bq or Ci tells how "active" this material is now.

5.2 Radiation Exposure:

The unit of exposure is the Roentgen (R). The Roentgen is defined by how gamma and x-rays interact in air. It is defined as the quantity of gamma or x rays which, when interacting with one kilogram of air, liberate energetic electrons that produce 0.000258 Coulombs of charge by ionization when the electrons are completely stopped.



5.3 Absorbed Dose

The absorbed dose is defined as the energy imparted by radiation per mass of absorbing material; the material here includes all types of exposed material. The absorbed dose is a quantity that refers to how much energy is deposited in material by the radiation. The term "RAD" is derived from the expression "Radiation Absorbed Dose".

The units are: 1 rad = 100 ergs/gram of material,
1 Gy (Gray, SI unit) = 1 Joule/kg of material, and
1 Gy = 100 rad.

5.4 Dose Equivalent

The dose equivalent is obtained by modifying the absorbed dose according to the types of radiation involved. The dose equivalent is the product of the absorbed dose and the quality factor (Q) of a given radiation (rad x Q). The quality factor is based on the type and energy of the radiation causing damage. It is based on the density of ionization along the radiation path. The quality factors for different types of radiation are: 20 for alpha, 1 for beta, gamma, and x-ray, 10 for neutrons of unknown energy (energy dependent), and 10 for high energy protons.

The dose equivalent units are: Rem (Roentgen Equivalent Man) = rad x Q, ie. 1 rad of alpha radiation = 20 rem or 0.2 Sv.

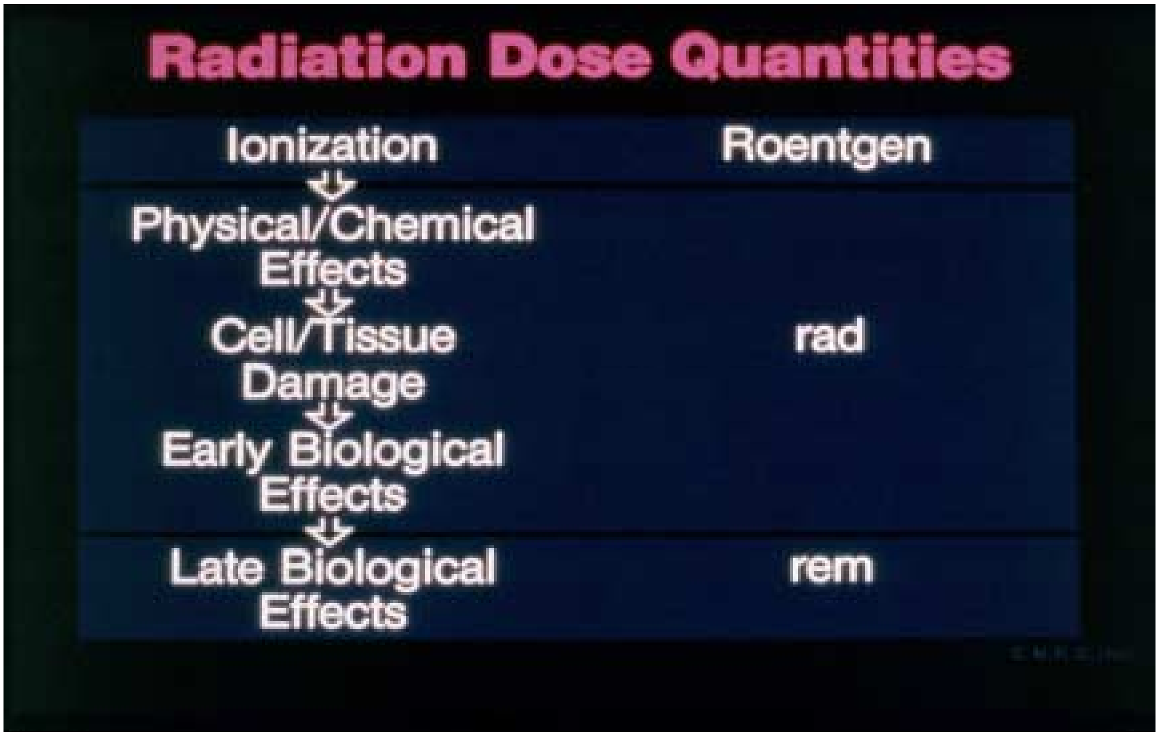
The rem (or Sv) is designed to be a unit of biological risk.

5.5 Effective Dose Equivalent (EDE)

Different organs or tissues in the body have varying degree of sensitivity to radiation. The tissue weighting factor (W_T) may be used to estimate risks, Effective Dose Equivalent (H_E), of a whole body exposure when radiation exposure is limited to only a portion of the body. For example, if a person's stomach receives 10 rem, the EDE is 1.2 rem (10 rem x 0.12).

Table 3. Tissue weighting factors, W_T

Tissue or organ	$W_{T,}$ ICRP60
Gonads	0.20
Bone marrow (red)	0.12
Colon	0.12
Lung	0.12
Stomach	0.12
Bladder	0.05
Breast	0.05
Liver	0.05
Esophagus	0.05
Thyroid	0.05
Skin	0.01
Bone surface	0.01
Reminder	0.05



6. Biological Effects of Radiation

As a principle of radiation protection, it is assumed that any amount of radiation is harmful, no matter how small the exposure is. This may be called "The Linear-No Threshold Theory". This theory is widely accepted as a principle of radiation protection even though it has not been proven.

6.1 Factors Determining Biological Effects of Radiation Exposure

The biological effects resulting from radiation exposure depend on a number of factors:

6.1.1 Total exposure:

How much exposure or dose has occurred to the tissue.

6.1.2 Exposure rate:

Our bodies have the ability to repair damage even during radiation exposure. How quickly radiation exposure is accumulated is important for both early and late biological effects.

6.1.3 Portions of the body exposed:

Some portions of the human body are more resistant to radiation than others due to their physiological function and cellular activity. Exposure to limited portions of the body have less effect than equal exposure to the whole body. A massive dose that would be fatal if delivered to the whole body might not even cause sickness if delivered to, for example, only the extremities.

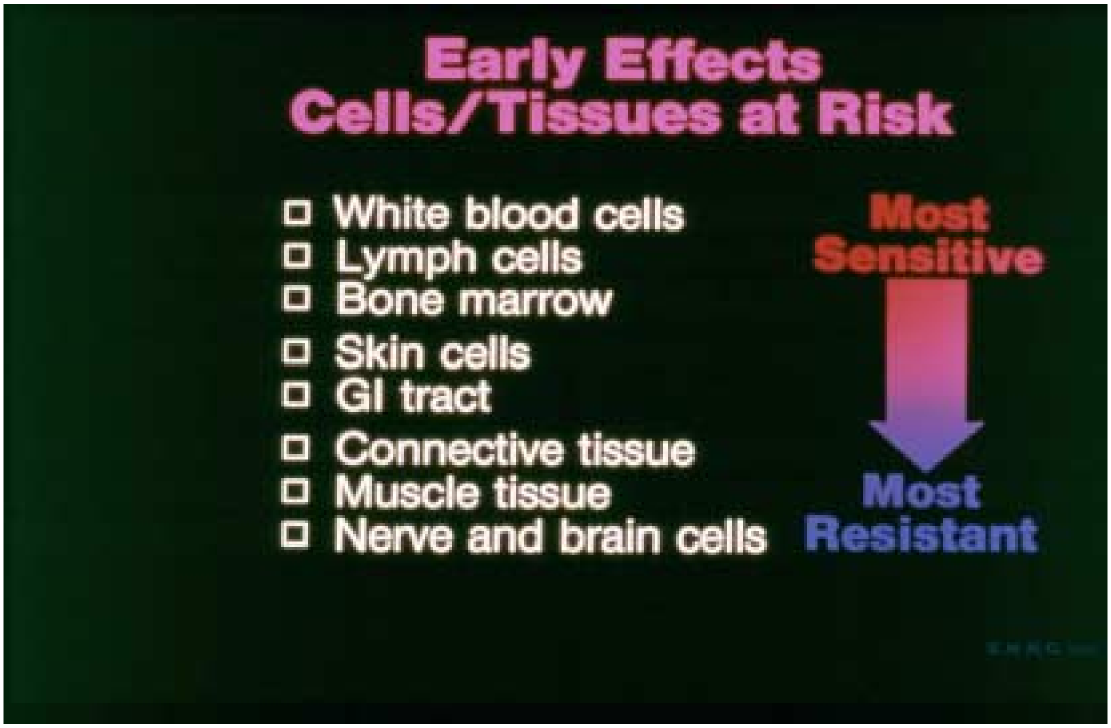
6.1.4 Type of Radiation Received:

The three main types of radiation, alpha, beta, and gamma have different penetrating abilities. Alpha radiation to external skin is no hazard because it is likely that the outer (dead) layer of the skin stops all alpha radiation. But if alpha radiation is received internally the damage to the surrounding tissue is expected to be 20 times more harmful than the expected damages from beta or gamma radiation. The Quality Factor (or Radiation Weighting Factor) for alpha is 20.

6.1.5 Biological Factors:

Age, sex, state of health, body size, body weight and other biological factors react differently to radiation exposure even under identical conditions. Actively dividing cells have increased sensitivity to radiation exposure.

6.2 Cell Sensitivity to Radiation



The sensitivity of cells and tissues to radiation exposure is commonly proportional to the rate of cell division. One type of cancer treatment is the use of radiation because cancer cells are multiplying at a rapid rate. Children are more sensitive to radiation than adults. Fetuses are especially sensitive to radiation exposure.

For an adult, white blood cells are most sensitive due to their rate of cell division. White blood cells, bone marrow, skin cells, and the gastrointestinal tract lining are very sensitive. Tendons, ligaments, and other connective tissues are moderately sensitive. Muscle, nerve cells, and brain cells are the most resistant cells in the body.

6.3 Radiation Effects on Live Cells

Radiation causes ionization that causes physical and chemical effects to the atoms and cells with which it interacts. Radiation passes through tissue and causes ionization within the cells of the tissue. The ions produced within the cell are electrically charged and chemically active. These charged, chemically active ions tend to react quickly with surrounding atoms and molecules of the cell and alter the cell structure and/or produce chemically active free radicals.

For an example, water is a primary constituent of a living cell. As a result of ionizing radiation interaction, the bonds between hydrogen and oxygen may be broken. The dissociated hydrogen and oxygen from water may not recombine as water molecules but may recombine in many different combinations between oxygen, hydrogen, and electrons i.e. H_2O_2, HO_2, OH, e-, etc.

Radiation interaction can happen in any location of a cell such as the DNA or the chromosome, which if damaged, could be fatal for the cell's survival. If a large enough cell population damage occurs, radiation effects may be immediate and fatal to the living organism. The radiation effects may show up in a matter of days, as acute effects, or years after the exposure, as latent effects.

6.4 Damaged Cell Repair Mechanism

Cells may be damaged by many factors such as life style, chemical exposure, radiation exposure, etc,. Most cells are capable of repairing damage including damage to the genetic material if given enough time (rate of exposure). But major damage might not be repaired and may result in cell death. Ability to repair damaged cells may depend on the type of chemicals produced by radiation in the cell and/or surrounding the cell.

If the chemicals produced are less active and stay away from genetic material (DNA) or other vital components necessary for cell survival, the cells would likely be less susceptible to radiation damage. The rate at which people recover from radiation exposure is not well known and variations among individuals are great.

6.5 Acute and Chronic Exposure

Acute exposure or an acute dose means the exposure is delivered in a short period of time. The exact time frame is not well defined but exposures received in hours or days are considered acute. The acute exposure does not necessarily mean a large and a lethal dose. It just mean a short time frame. Chronic exposure is exposure spread out through a longer period of time.

6.5.1 Acute Effects (Acute Radiation Syndrome), Delayed Somatic Effects, and Genetic Effects

A sufficiently large (hundreds of rems) acute radiation dose to the whole body can cause severe biological damage to the body or death. Acute radiation syndrome is the collection of symptoms and effects characteristic of massive radiation exposure. The symptoms of radiation sickness may vary largely but the gross symptoms are vomiting, nausea, diarrhea, fatigue, and decrease in blood counts:

Note: rad and rem may be interchanged for this listing.

< 25,000 mrem (0.25 Sv): No obvious effects,

80,000-120,000 mrem (0.8-1.2 Sv): Vomiting and nausea for about 1 day to 5-10 percent of exposed people, fatigue but no serious disability, lower blood counts, i.e. white and red blood cell.

130,000-220,000 mrem (1.3-2.2 Sv): Vomiting, nausea for about 1 day, followed by radiation sickness in about 25-50% of personnel. No death anticipated.

270,000-330,000 mrem (2.7-3.3 Sv): Vomiting, nausea in nearly all personnel on first day, followed by other symptoms of radiation sickness. About 20% deaths within 2-6 weeks.

400,000-500,000 mrem (4-5 Sv): Vomiting, nausea in all personnel on first day, followed by other symptoms of radiation sickness. About 50% deaths within 1 month.

500,000-750,000 mrem (5-7 Sv): Vomiting, nausea in all personnel within 4 hours, followed by other symptoms of radiation sickness. Up to 100% deaths. Few may survive.

>1,000,000 mrem (10 Sv): Vomiting, nausea in all personnel within 1-2 hours, followed by other symptoms of radiation sickness. No survivors expected.

Delayed somatic effects are biological effects which appear in the exposed persons but may take a long time to show up. Examples are development of cancer, life shortening, and cataracts. Somatic effects can be stochastic or non-stochastic.

Genetic effects are the radiation exposure effects manifested in the offspring of exposed parent(s).

6.6 Database of Biological Effects of Radiation Exposure

6.6.1 Natural Background Radiation Exposure

Energetic radiation from outer space and the sun are continually bombarding us. Soil contains naturally radioactive material such as potassium, uranium, thorium, and their progenies. Radon, one progeny of uranium and thorium, contributes the largest natural radiation exposure to humans. The background radiation exposure may vary with location due to differing radionuclide concentrations in rock and soil, water, and an increase of cosmic radiation with altitude. The food we eat, the water we drink, and the air we breath contains radioactive material. Total average annual effective dose to members of the US population is estimated to be 300 mrem per year (3 mSv/year). Additionally, man made radiation sources such as medical x rays and nuclear medicine contributes about 60 mrem per year (0.6 mSv per year) exposure to Americans. The average effective annual dose equivalent from all sources to members of the US population is 360 mrem.

Naturally Occurring Long-lived Radionuclides in Human Body

Isotope	$_{238}U$	$_{226}Ra$	$_{228}Ra$	$_{210}Pb$	$_{210}Po$	$_{40}K$	$_{14}C$	$_{3}H$	$_{87}Rb$	$_{90}Sr$
Activity, pCi	26	120	50	600	200	130,000	87,000	27,700	29,000	2,886

The total radioactivity in the body is 277,582 pCi. This is 10,270 radioactive decays per second (dps) and 887,374,138 (887 million) disintegration per day in the body. Each radioactive decay produces radiation.

Source: Radiation Protection (pages 56, 370), Shapiro, 1990, Harvard Press.

Natural Radioactivity in a Banana

Bananas are a good source of potassium, a very important nutrient. All natural potassium contains 0.0117% potassium-40 (40K) which is radioactive potassium. A medium size banana contains about 451 mg of potassium. The amount of 40K contained in a banana is 0.0528 mg. This is equivalent to 14 dps or 0.00037 uCi. The dose equivalent, if a banana is eaten, is about 0.01 mrem. Sometimes this is called the banana equivalent dose.

Sources: Food Values of Portion Commonly Used, 16th edition, Bosen and Church.
Chart of Nuclide, F. William Walker et al.

6.6.2 Low Level Radiation Exposure Studies

Background radiation exposes the entire world population. Due to that reason alone, it is very difficult to determine the effects of low level radiation exposure. More information is available about high level exposure and its effects. Radiation effects in low level exposure is extrapolated from the high level exposure. Regulatory Guide 8.29 from the US Nuclear Regulatory Commission stated that there is a risk of 4 in 10,000 of a 1,000 mrem (0.01 Sv) dose causing a fatal cancer". Because the effects of low level radiation are not well known, it is assumed that any amount of radiation is harmful, no matter how small it is. This is not a proven fact but widely accepted.

However, there have been studies which have reported a beneficial effect of low level radiation exposure. One study was conducted in areas of Yangjiang, China where the background radiation is 2.64 times higher than the average background level. The group of population who lived there more than 6 generations was studied and compared to a similar life style population group with average background radiation level. The period of study started in 1972 and lasted until 1986. This study examined the cancer mortality data between 1970 to 1986 and observed over one million person-years in each area of the high background and the controlled area (CA).

The back ground radiation in the high background area was 547 mrem (5.47 mSv) per year and 207 mrem (2.07 mSv) per year in the controlled area. The study concluded that "No increase of cancer mortality has been found in high background radiation area (HBRA), but on the contrary, there was a tendency for the cancer mortality in HBRA to be lower than that in CA...It is likely that there may be a dose threshold for cancer incident, but this remains to be determined by further research."

Dr. Bernard L. Cohen studied lung cancer mortality rates and average radon concentration in homes in 1601 US counties to "Test the Linear-No threshold Theory...". Dr. Cohen stated in the paper "... there is a strong tendency for lung cancer rates to decrease with increasing radon exposure, in sharp contrast to the increase expected from the theory. There is now a substantial body of evidence indicating that the low level radiation does indeed stimulate such biological defense mechanisms...". The beneficial effects of low level radiation are not generally accepted.

6.6.3 Uncertainties associated with the Low Level Exposure

The National Research Council in BEIR V report stated "In this report it is estimated if 100,000 persons of all ages received a whole body dose of 0.1 Gy (10 rad) of gamma radiation in a single brief exposure, about 800 extra cancer deaths would be expected to occur during their remaining lifetimes in addition to the nearly 20,000 cancer deaths that occur in the absence of the radiation. Because the extra cancer deaths would be indistinguishable from those that occurred naturally, even to obtain a measure of how many extra deaths occurred is a difficult statistical estimation problem." It is assumed that radiation is harmful even at low levels but there are high uncertainties associated with this assumption and it has not been proven.

6.6.4 High Level Radiation Exposure Studies

A lot more data is available in high level radiation exposure studies: A large number of bomb survivors after world war II in Japan, patients who received a large amount of medical use radiation during 1930's to 50’s, a few hundred radium dial painters, uranium minors, and animal studies have been examined. Radiation effects of high level exposure are reasonably well established.

7. Radiation Exposure Standard (NAC 459.325)

Occupational Dose Limits:

Whole body (Total Effective Dose Equivalent) = 5 rem/year,
Sum of individual organs or tissue = 50 rem/year,
Eye dose (lens of eye) = 15 rem/year,
Skin or any extremity = 50 rem/year,
Dose to embryos of declared pregnant woman* = 0.5 rem for the
entire pregnancy, and
Minors = 10% of above limits.
Member of public = 0.1 rem/year.

* Declared Pregnant Woman means a woman who has voluntarily informed her supervisor, in writing, of her pregnancy and the estimated date of conception. The declaration remains in effect until the declared woman withdraws the declaration in writing or is no longer pregnant.

Note: Average Americans receive about 300 mrem per year from natural background and 60 mrem from medical exposures.

8. External Radiation Protection

External radiation can be reduced by limiting the duration of an exposure period, increasing the distance between the external radiation source and the person, and placing a shielding material between the external radiation source and the person.

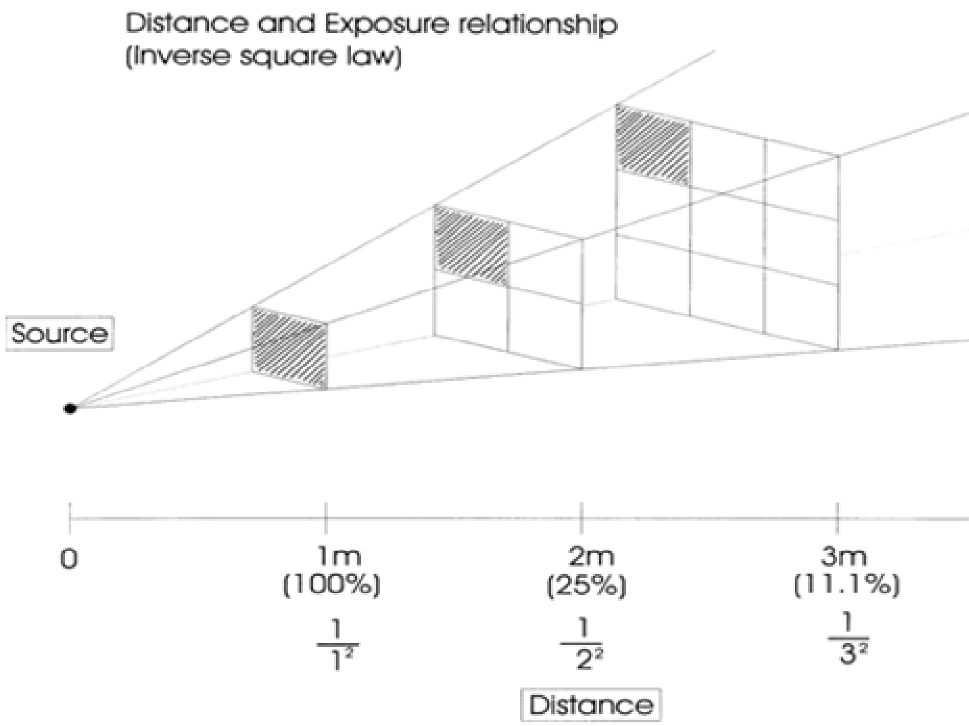
8.1 Time, Distance, and Shielding

Time

Radiation exposure can be reduced by minimizing the time of exposure. Practice runs without source may help to reduce exposure times when an actual experiment is performed. If limitation of the stay time in the vicinity of an external radiation source is not possible due to the required time to perform a given task, then other means of exposure reduction should be utilized.

Distance

Distance is a simple, inexpensive, and very effective method of dose reduction. The intensity of radiation from a point source decreases by $1/(\text{distance})^2$. If a distance between a person and a source is doubled (x2) then the exposure rate is decreased by 4. This is called the "Inverse Square Law".



Example. An exposure rate is 100 mR/h at 1 meter. What is the expected exposure at 2 meter, 3 meter, and 4 meter?

$RD^2=rd^2$, where
R: exposure rate at distance D,
r: exposure rate at distance d, and
D, d: distances from a fixed point source.

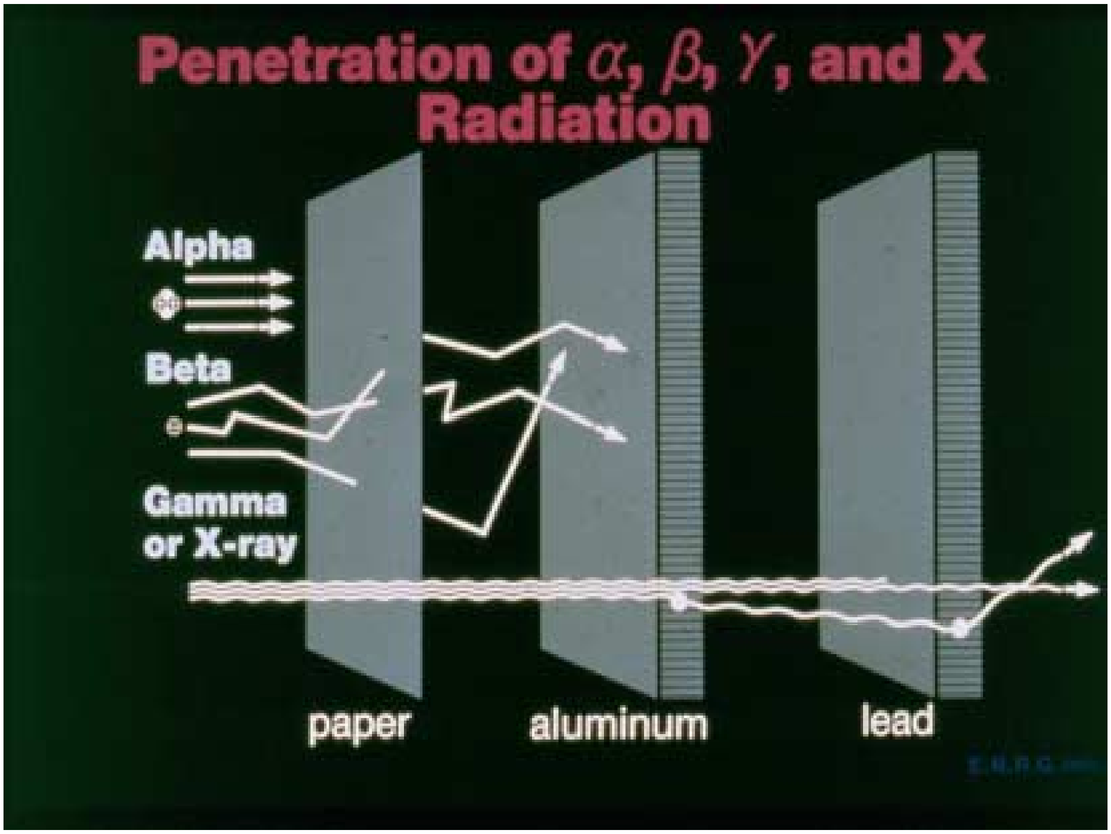
at 2 meters,
r=(100 mR/hr)/4=25 mR/hr.

at 3 meters,
r=(100 mR/hr)/9=11.11 mR/hr.

at 4 meters,
r=(100 mR/hr)/16=6.25 mR/hr.

Shielding

Shielding is to place a material which will interact with radiation between a source and a person (or location of interest) to reduce exposure. Alpha radiation requires no shielding. High Beta radiation can be effectively shielded by low atomic number material such as lucite and plastic. Gamma and x-rays require a high density material such as lead. Shielding can be very effective to reduce exposure but it may be expensive. Shielding material selection is dependant on the type and energy of radiation.



8.2 Security of radioactive material

All radioactive material under UNR license must always be under the surveillance of the user, or kept locked. Radioactive material must be kept in designated areas and the area must be posted accordingly.

8.3 Amount of radioactive material

Radiation is directly proportional to the amount of radioactive material present. The smallest possible amount of radioactive material is to be handled whenever practical.

9. Internal Radiation Protection, Contamination Control and Monitoring

Radioactive material can enter into body via ingestion, inhalation, or intact or damaged skin. Unlike an external radiation field which can be avoided by time, distance, and shielding, radiation sources inside the body are out of our direct control. There are NOT many ways to eliminate internal sources. Biological removal and physical decay are the only ways to elimination. Therefore, the best defense against internal contamination is to prevent intake by blocking intake pathways.

9.1 Contamination

Contamination is presence of radioactive material in any place where it is not necessary. It may cause unnecessary radiation exposure and/or poses a possible intake pathway.

Contamination Control

The work area where radioactive material is used should be monitored before and after use of radioactive material. The surrounding area should be monitored periodically. The monitoring results need to be recorded for future reference. Always work over trays or work surfaces lined with an absorbent material. Keep and transport radioisotope doubly contained. Label radioisotope containers with your name, date, radionuclide and its quantity. No eating, drinking, smoking or application of cosmetics is permitted in a radioisotope laboratory. Wash hands after handling radioisotope and before doing other work. Always use rubber or plastic gloves when handling radioisotope. Lab coats and safety goggles shall be worn in the laboratory and left in the laboratory. They shall not be used for other work, sent to another area, or released for cleaning until demonstrated to be free of contamination. No open toe shoes are allowed while handling radioisotope.

Contamination Monitoring

A widely used contamination monitor is thin window GM detector. A GM detector called "pancake GM" has a wide detector area (2 inch in diameter) with a thin window. This probe can detect alpha, beta, and x, gamma rays. Most of radiation types used in research laboratories may be detected by a pancake detector. Its high sensitivity makes it easy to use in a low level contamination area. All new contamination monitors are equipped with audible sound which allows the user to focus on the area being monitored. Normally contamination can be identified by listening to the detector sound. When monitoring surface area for contamination, the active detector area should be close to the surface without touching it and move slowly over the monitoring area about an inch per second. Swipe surveys are another method of monitoring contamination. A filter paper, filter cloth, or q-tip are used to take wipe samples which are analyzed by an appropriate analyzer. For example, hydrogen-3 (a weak beta emitter) can be monitored by swipe surveys. Liquid scintillation counting is a common method to analyze hydrogen-3 swipes.

Decontamination

Contamination may be associated with buildings, equipment, and personnel. If contamination is found, the contamination should be removed as soon as possible. All personal who are affected must be notified to avoid the spreading of contamination and to minimize potential radiation exposure. The Radiation Safety Office can provide assistance if a problem persists. It is easy to remove contamination in workbench tops if the work area is covered with plastic backed absorbent pad. Application of a new pad and discarding the contaminated absorbent pad into a radioactive waste container takes care of the contamination. This is one of the reasons all radioactive material handling areas such as bench tops should be covered with plastic backed absorbent pads.

Personnel Decontamination

Personnel contamination such as on clothing, shoes, or a part or whole body should be approached in such a way as to prevent spreading of contamination and keeping it away from wounds. Water and mild soap should be used initially. If harsher methods are needed due to stubborn contaminants, an evaluation should be made to avoid embedding the contaminant deeper into the skin. If contamination is fixed and not removable, the contaminated area should be marked accordingly. An evaluation should be made based on the isotope amount, half life, radiation type, and occupancy of the area, etc, to correct contamination. It may be practical to wait for decay, or, to remove the contaminated area/equipment. After decontamination, the result and its effectiveness must be verified by re-survey.

9.2 Internal Dosimetry (monitoring methods of personnel suspected of having radioactive material intake)

Bioassays include such tests as radioanalysis of blood, urine, fecal samples, nose swabs or of sputum. In addition the term bioassay includes whole body or thyroid counts. As a general principle, bioassays will be required after any incident (e.g., contamination of personnel or exposure of persons to airborne radioactivity) where the possibility of internal deposition of radioisotopes exists.

Urine analysis is a commonly used method for monitoring personnel suspected of having or with high potential of radioactive material intake. Urine sample is collected post radioactive material use and analyzed by appropriate radiation system. The most commonly used instrument for urine analysis is Liquid Scintillation Counter.

For personnel who use radioactive iodine, direct measurement of person's thyroid is a common bioassay method.

In addition to the above bioassay requirement, bioassays are required for one time tritium use greater than 10 mCi and use of unbound radioiodine greater than 1 mCi at one time. Bioassay service is available at any time upon the request of the User. Bioassays may be arranged by calling the EH&S at 784-4540. Bioassay need to be performed within a few days from the radionuclide use.

10. Emergency Procedures

Any medical emergency takes priority over a radiological emergency. Radioactive materials used in research at UNR cannot produce life threatening levels of radiation under any circumstances.

The objectives for handling radiological emergencies are to assist injured personnel, minimize the radioactive material entering into human body, prevent the spread of contamination, and remove the contamination as soon as possible. When approaching radiological emergencies, it is recommended to apply these objectives using standard laboratory safety precautions, and a common sense approach because it is not possible to address all possible emergency scenarios.

Decontamination and/or spill clean-up in a radiation use facility is the responsibility of the Authorized User of the facility. The EH&S Department will provide assistance where needed.

All radiological incidents are to be reported to EH&S as soon as practical with the exception of easily cleaned minor contamination. All incidents must be documented. This documentation must include the final survey indicating that all contamination has been removed.

10.1 Personnel decontamination

Contaminated areas of the body need to be identified using appropriate survey methods. Do not use any decontamination methods which may spread material, increase penetration into the body, or spread to wounded area.

Loose particles may be removed by gently applying adhesive side of tape to the particles attached to skin. Most contamination may be removed by running water over the contaminated area. Use soap or detergent if water by itself doesn't remove all the contaminants. Avoid harsh scrubbing which may increase skin penetration. If contamination persists, stronger decontamination methods may be necessary after first consulting with the EH&S Department.

10.2 Minor spills or contamination

Most incidents at UNR will likely involve small quantities of radioactivity. If less than 20 microcurie of radioactivity is involved in a spill or contaminations, it is considered a minor. Commercial cleaning supplies should be adequate. It is recommended to use them only when other measures such as plain water did not work. The following steps are recommended;

- Warn others in the lab that a spill or contamination has occurred.
- Fresh new gloves should be worn to protect hands and avoid spread of contamination.
- Use paper towels or absorbent paper to prevent spread.
- Mark off the contaminated area.
- Do not allow lab personnel to leave the area without first being monitored.
- Secure all contaminated items in sealed containers to prevent spread of contamination

10.3 Major spills

It is considered a major spill if greater than 20 microcurie of radioactive materials are spilled or if personnel are contaminated. It is not possible to address all types of accidents. But the following steps are general guide lines to deal with major accidents:

- Upright or cut off the release of radioactivity from the source if possible.
- Minimize radiation exposure to personnel.
- Minimize contamination from spreading.
- If airborne radioactivity is possible, shut off ventilation, hood, and close windows if possible.
- Secure all contaminated items to prevent spread of contamination.
- Secure the contaminated area.
- Report incident to EH&S.
- Remain in the general area until EH&S personnel arrive.